High Intensity Muon Beam (HIMB) Project at PSI

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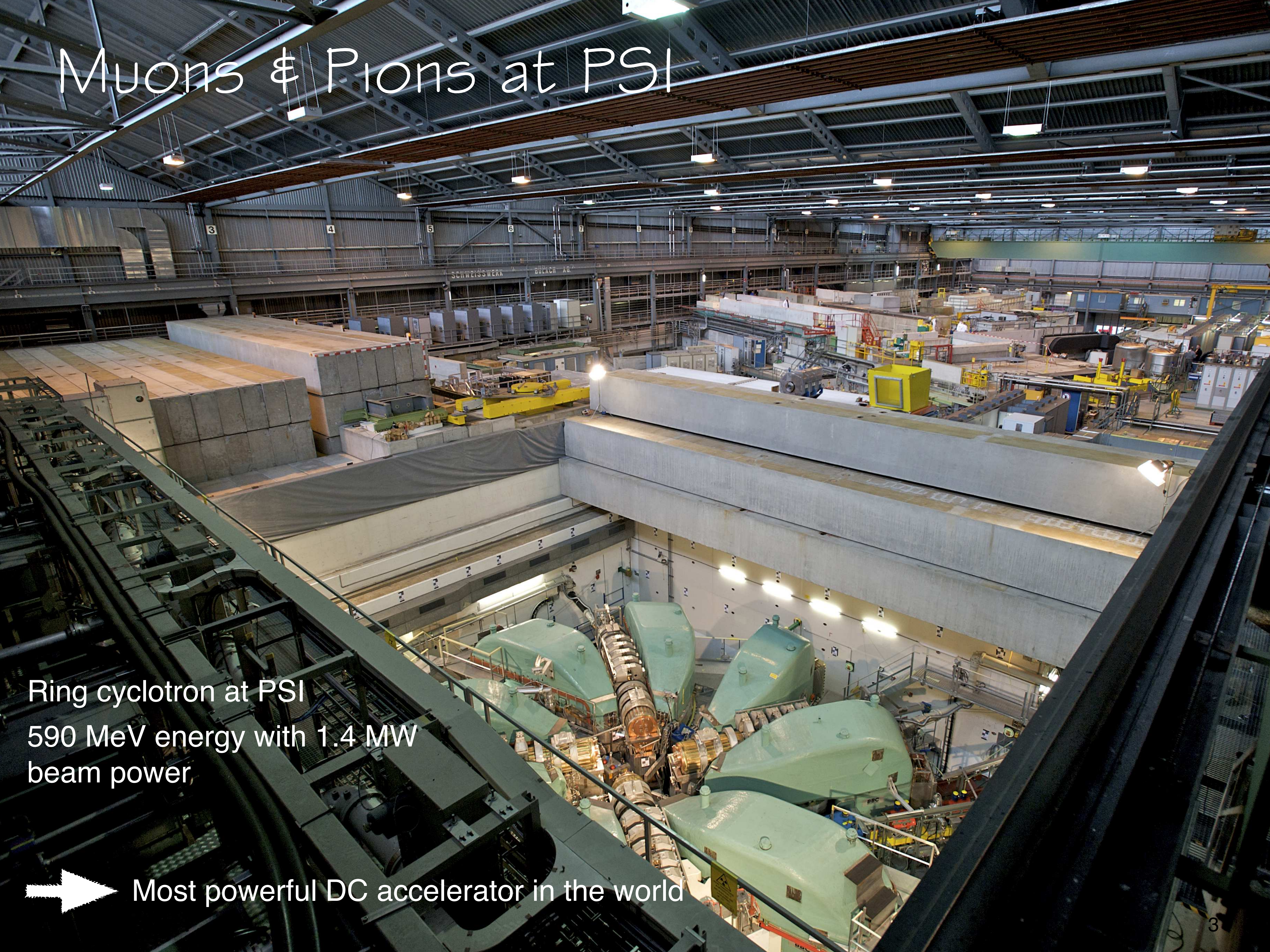
Paul Scherrer Institute

cLFV Snowmass-2021
Zoom
10. 12. 2020

Location of Paul Scherrer Institute

Muons & Pions at PSI

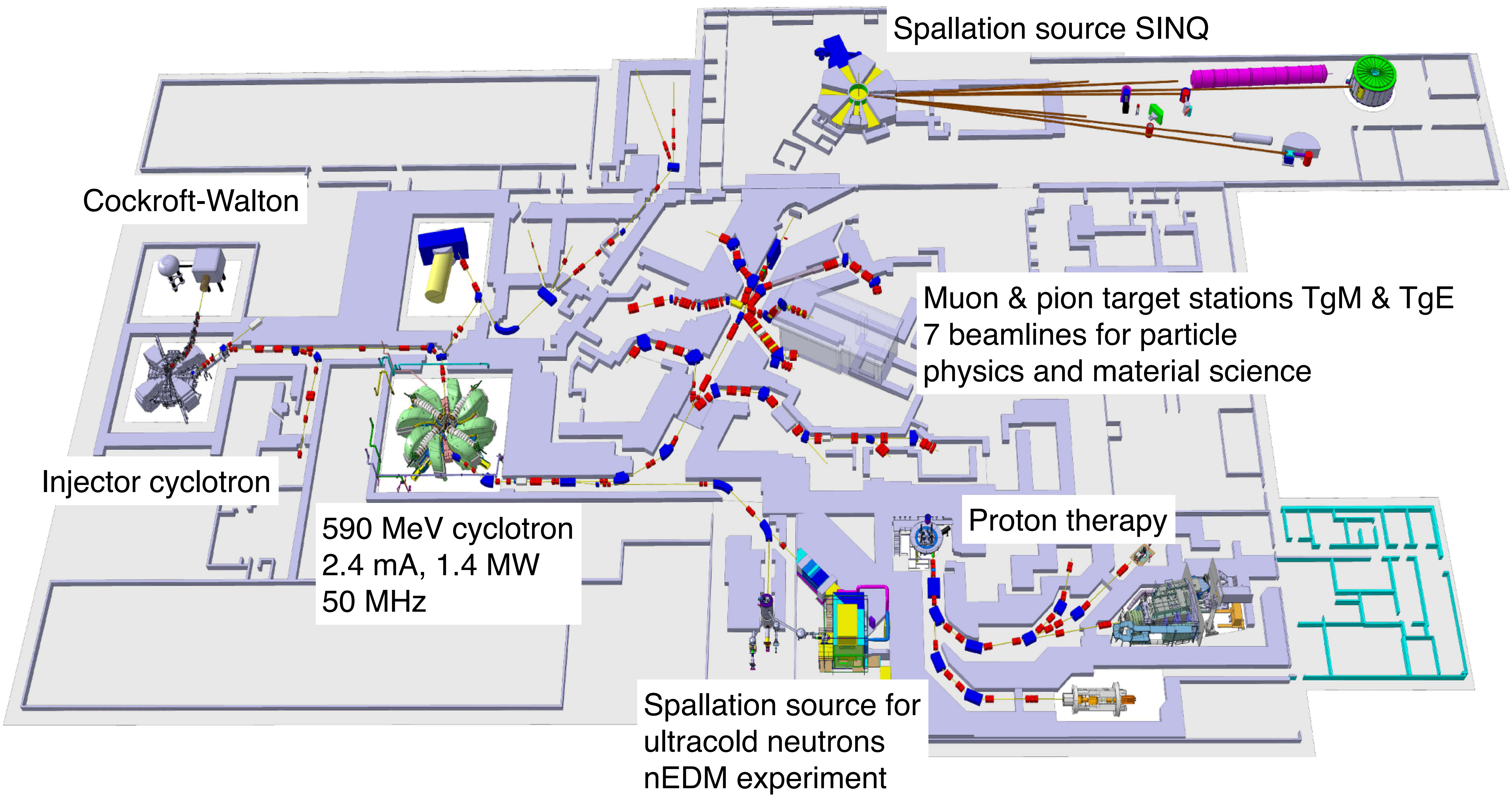


Ring cyclotron at PSI

590 MeV energy with 1.4 MW beam power

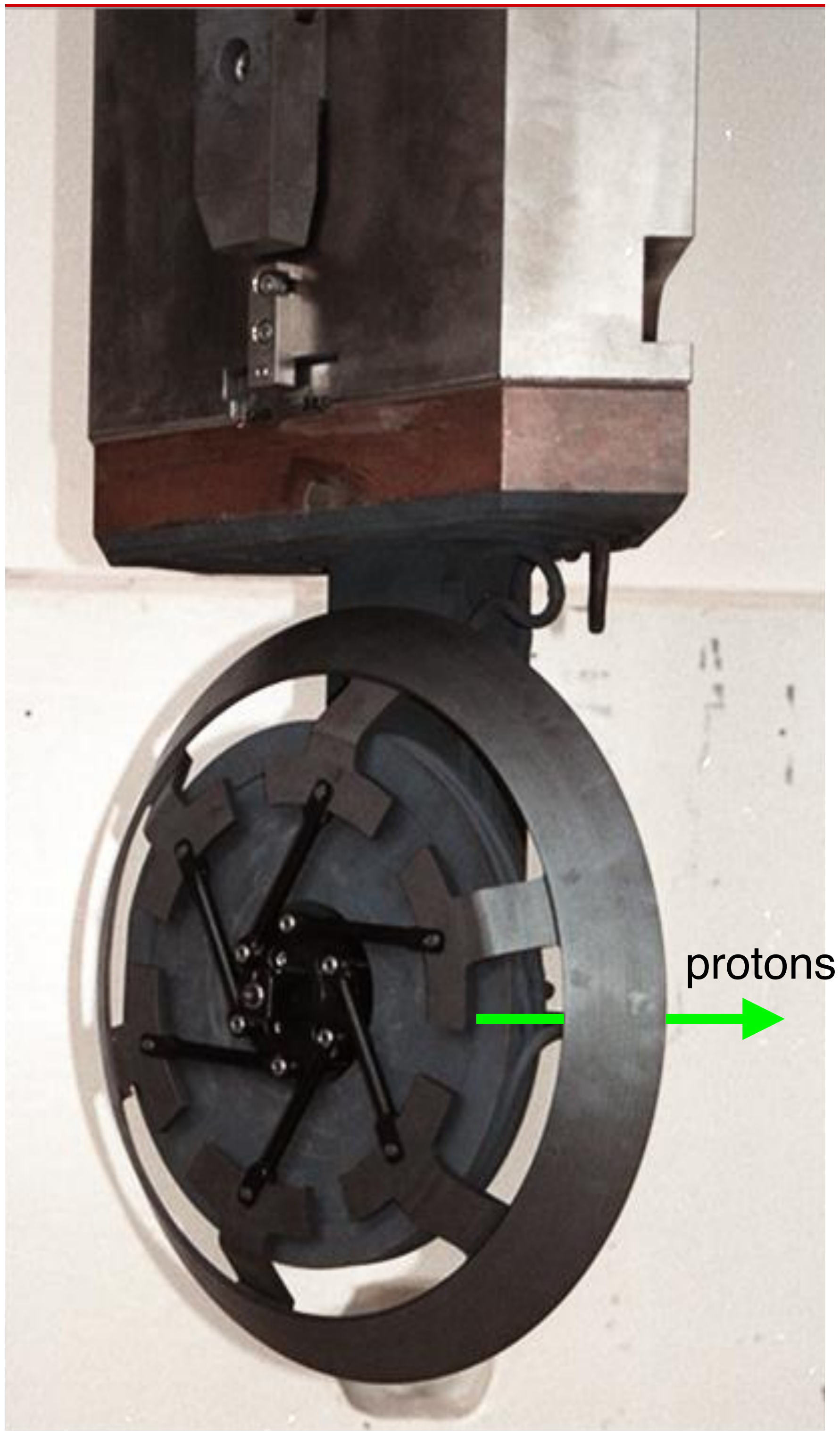
→ Most powerful DC accelerator in the world

PSI Proton Accelerator HIPA



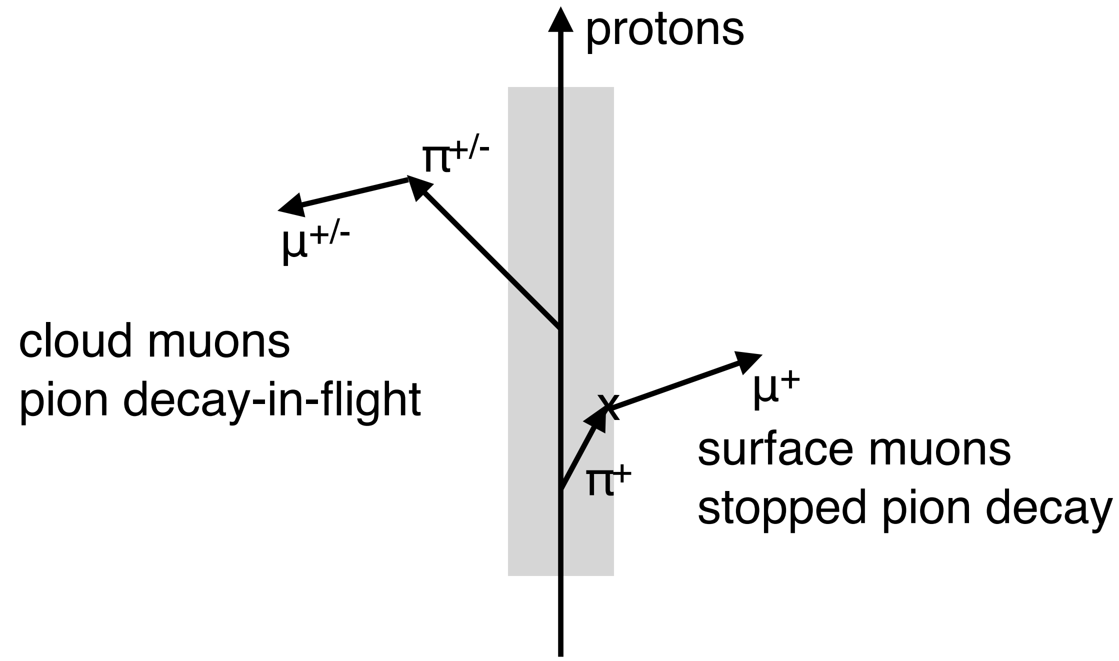
Production Target TgE

- 40 mm polycrystalline graphite
- ~40 kW power deposition
- Temperature 1700 K
- Radiation cooled @ 1 turn/s
- Beam loss 12% (+18% from scattering)



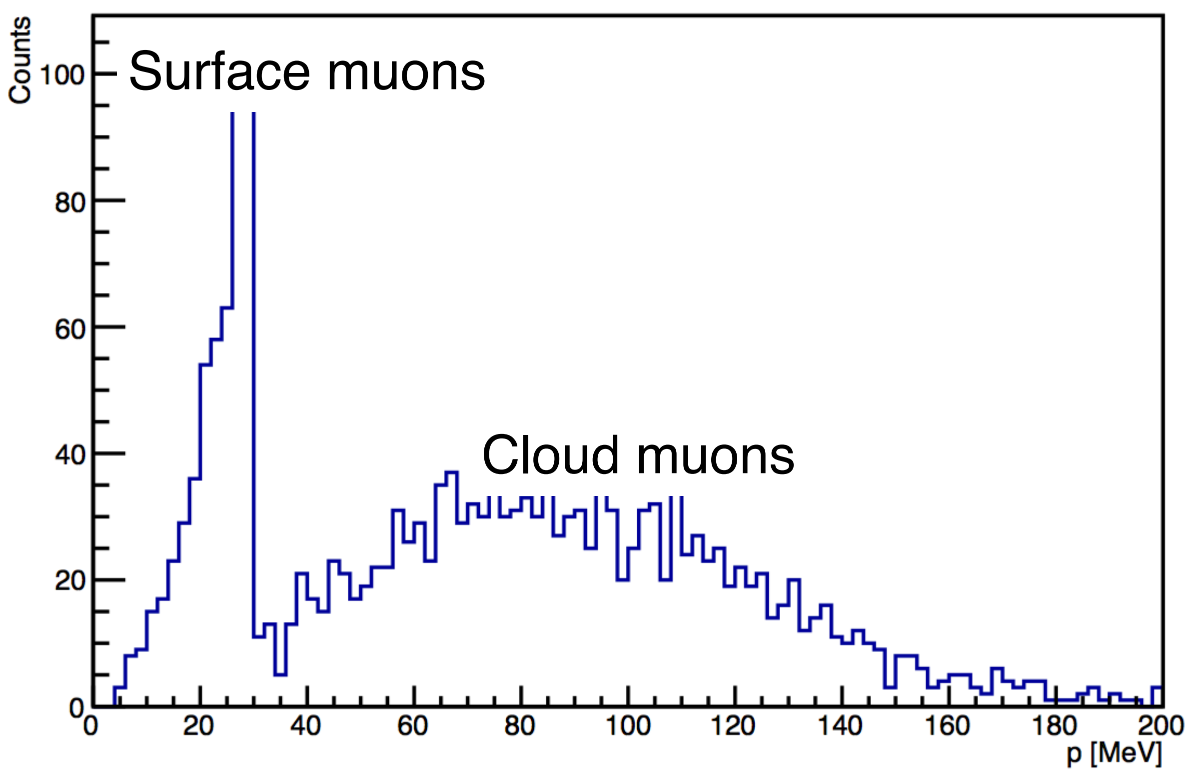
Pions, surface and cloud muons

- Pions produced through the interaction of the protons with the target
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons
- 50 MHz beam structure for pions and cloud muons
- For surface muons: time structure of cyclotron smeared out by pion lifetime → DC muon beams

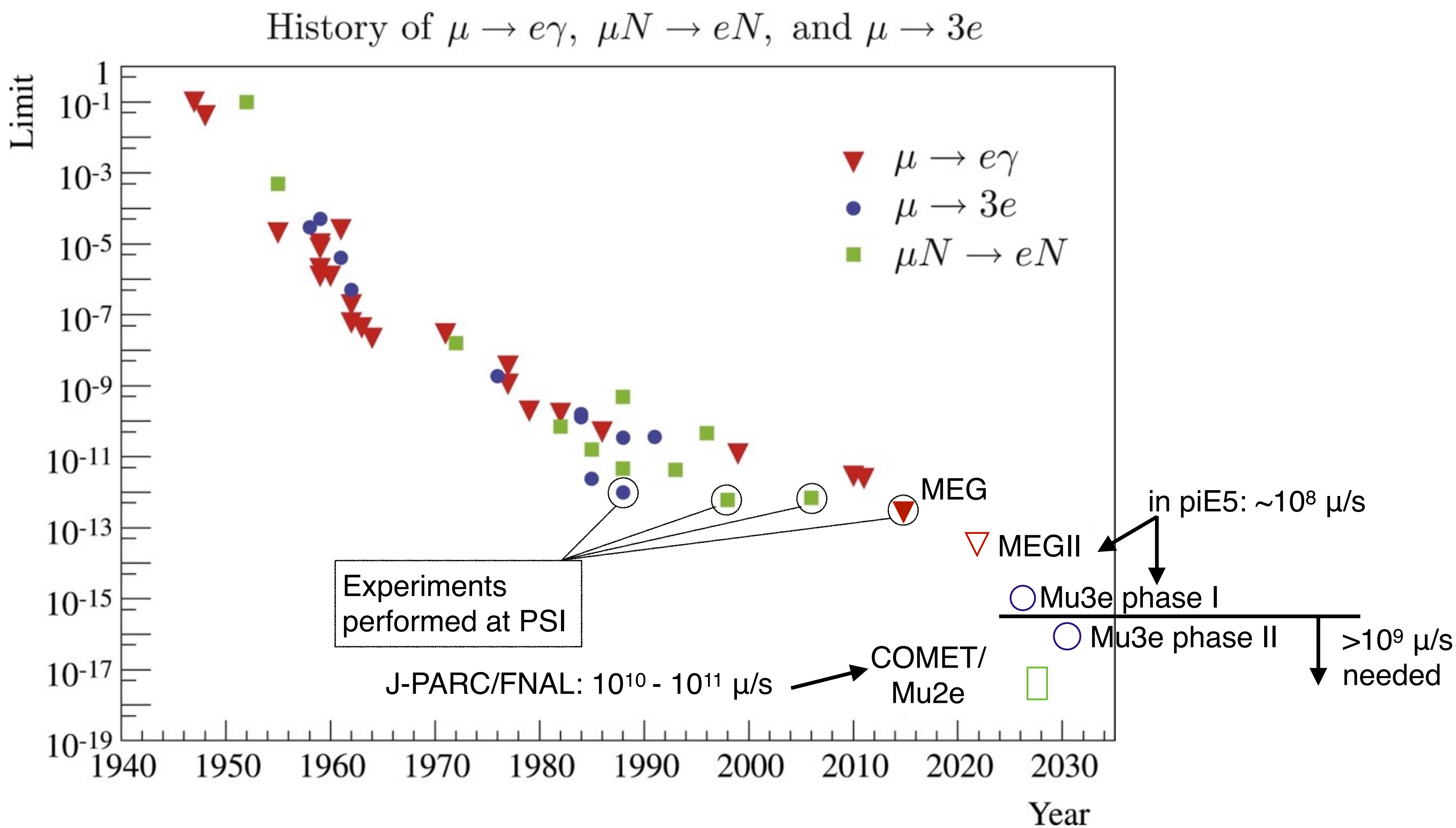


$$p + p \rightarrow p + n + \pi^+$$
$$p + p \rightarrow p + p + \pi^0$$
$$p + p \rightarrow d + \pi^+$$

$$p + n \rightarrow p + n + \pi^0$$
$$p + n \rightarrow p + p + \pi^-$$
$$p + n \rightarrow n + n + \pi^+$$
$$p + n \rightarrow d + \pi^0.$$



Motivation: cLFV as an example



- Neutrinoless muon decays (cLFV) one of the most sensitive probes for new physics
- $\mu^+ \rightarrow e^+\gamma$ & $\mu^+ \rightarrow e^+e^-e^+$ only possible at DC & intensity-frontier machine such as HIPA

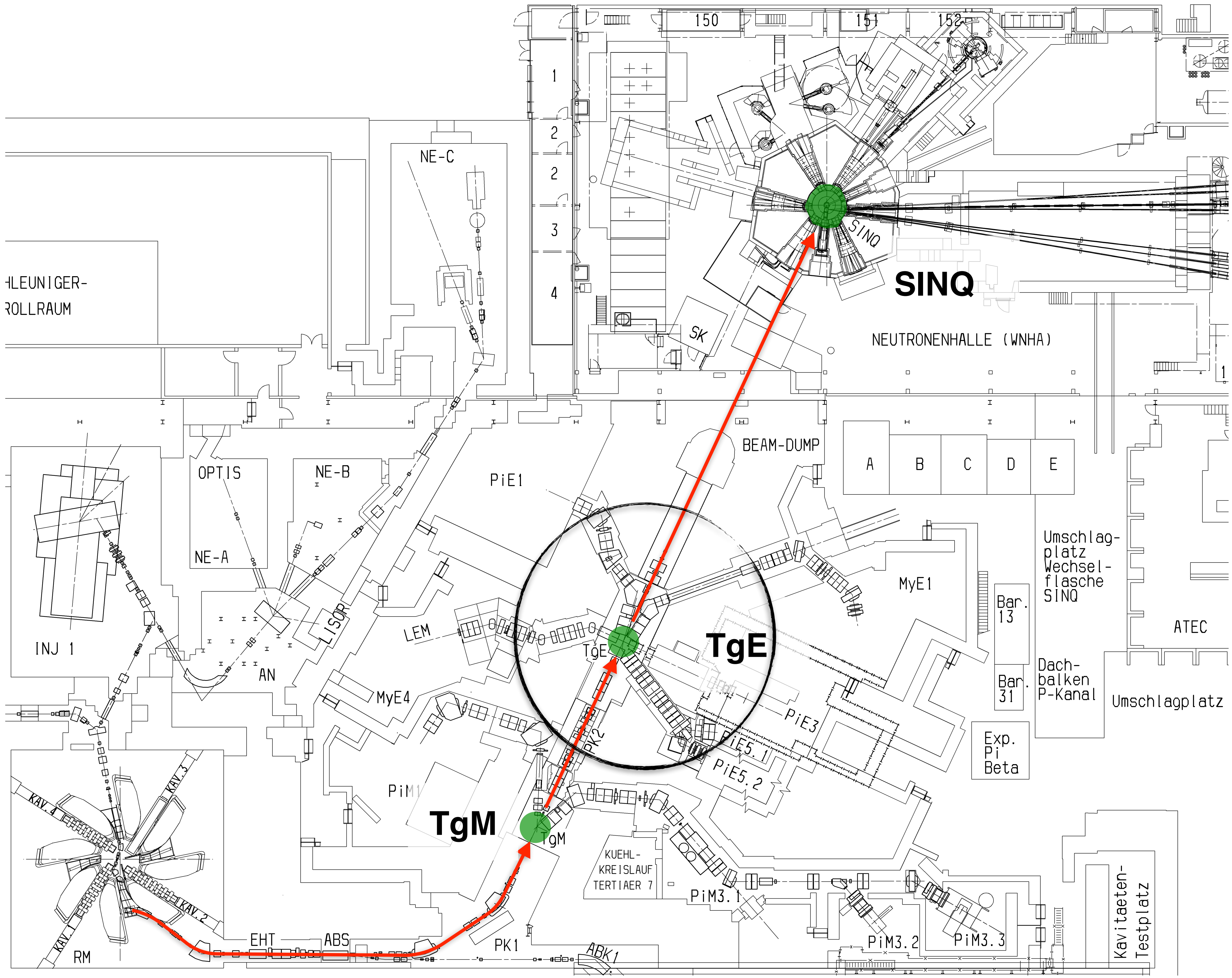
⇨ HiMB project aims at delivering 10^{10} μ^+/s at PSI for particle physics & μSR

Science Case

- **Particle physics:**
  - HIMB only:
    - Mu3e
    - MEG
    - Mu-Mubar Oscillations
    - Muonium spectroscopy, interferometry & gravity
    - Muonic atom spectroscopy
    - Atomic parity violation with muons
    - Beyond SM searches with positrons
  - HIMB + muCool:
    - Muonium spectroscopy, interferometry & gravity
    - Muon reacceleration
    - Muon EDM (needs reacceleration)
    - g-2 (needs reacceleration)
  - …
- **μSR:**
  - High-rate: vertex reconstruction (pixel detector based μSR) to break pile-up limitation
  - Microbeams (collimation or with reaccelerated beam) enabling the possibility to measure small samples or perform ultrahigh pressure measurements
  - Possibly improve LEM rates
  - Possibly multiple instruments on same beamline
  - …

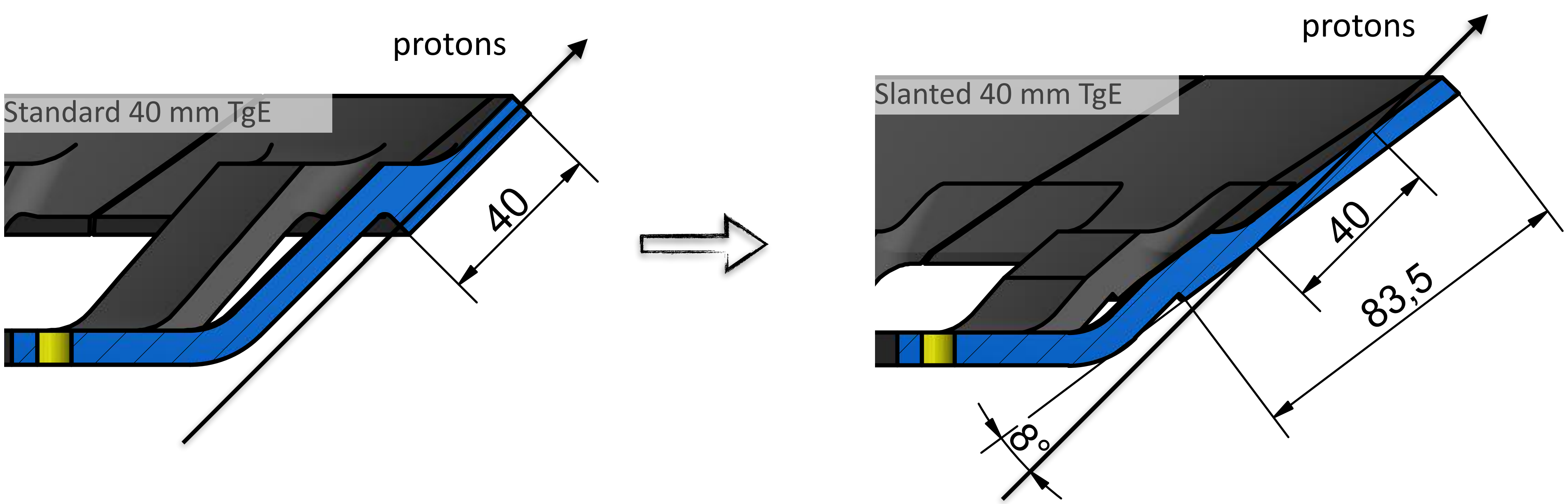
Floorplan PSI

PAUL SCHERRER INSTITUT PSI



HIMB Slanted Target Design

- Change of TgE geometry to increase surface muon rates for all connected beamlines
- Increase safety margin for “missing” TgE with proton beam



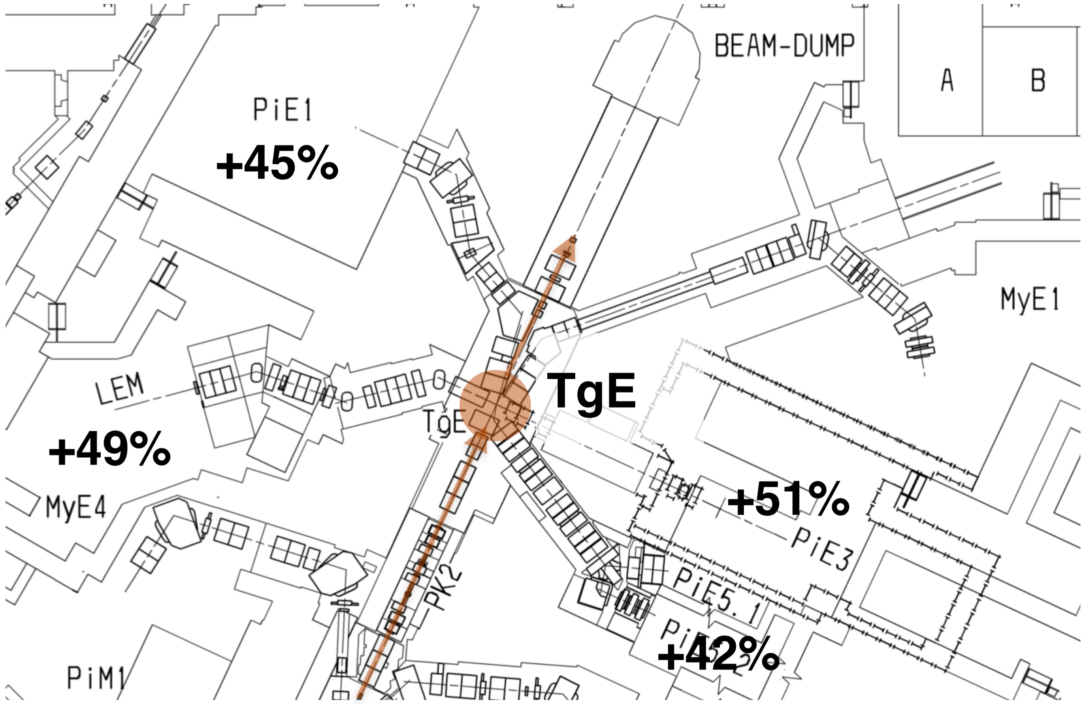
HIMB Slanted Target Tests

- HIMB 40 mm slanted target installed on 25. 11. 2019

Muon beam rates:

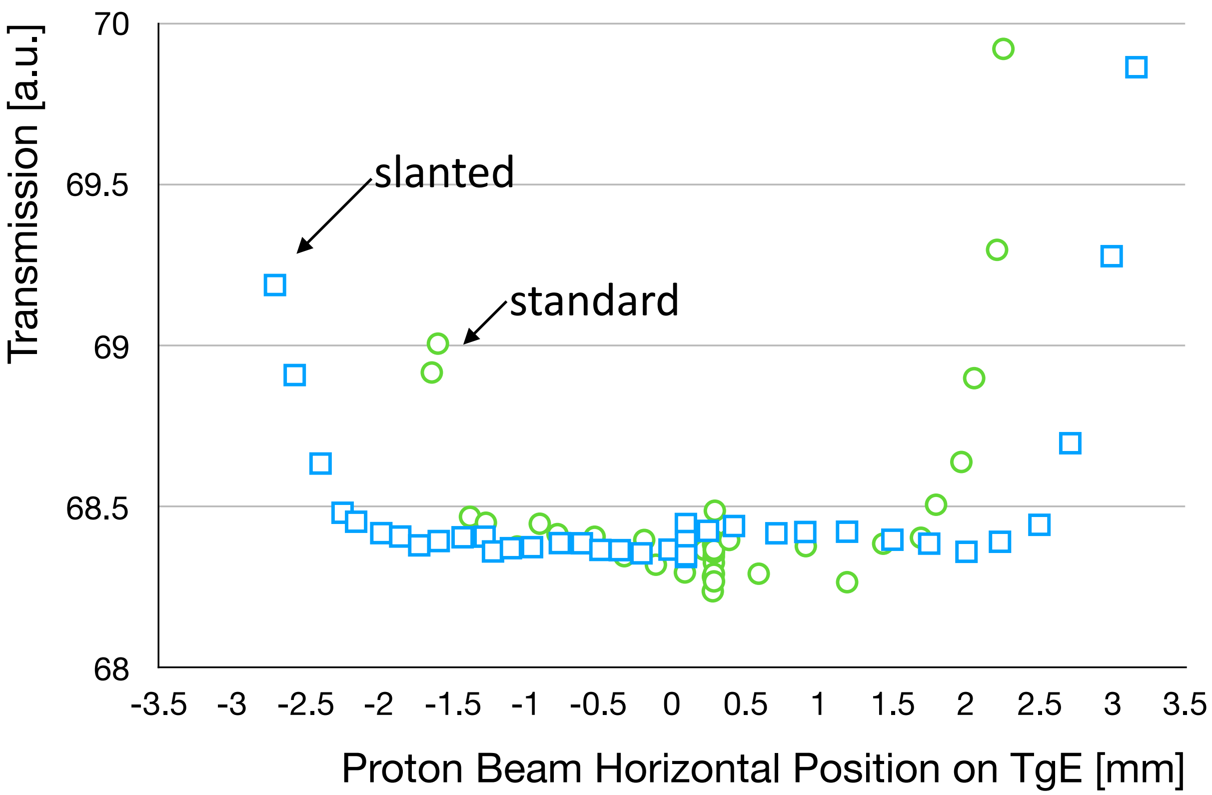
- 40-50% increase in surface muon rate measured in µE4, πE5, πE3 and πE1 (µE1 not affected as it relies on pion collection)
- Consistent with simulation to within 10%

> 40 mm slanted target as good or better than 60 mm standard target!



Proton beam impact:

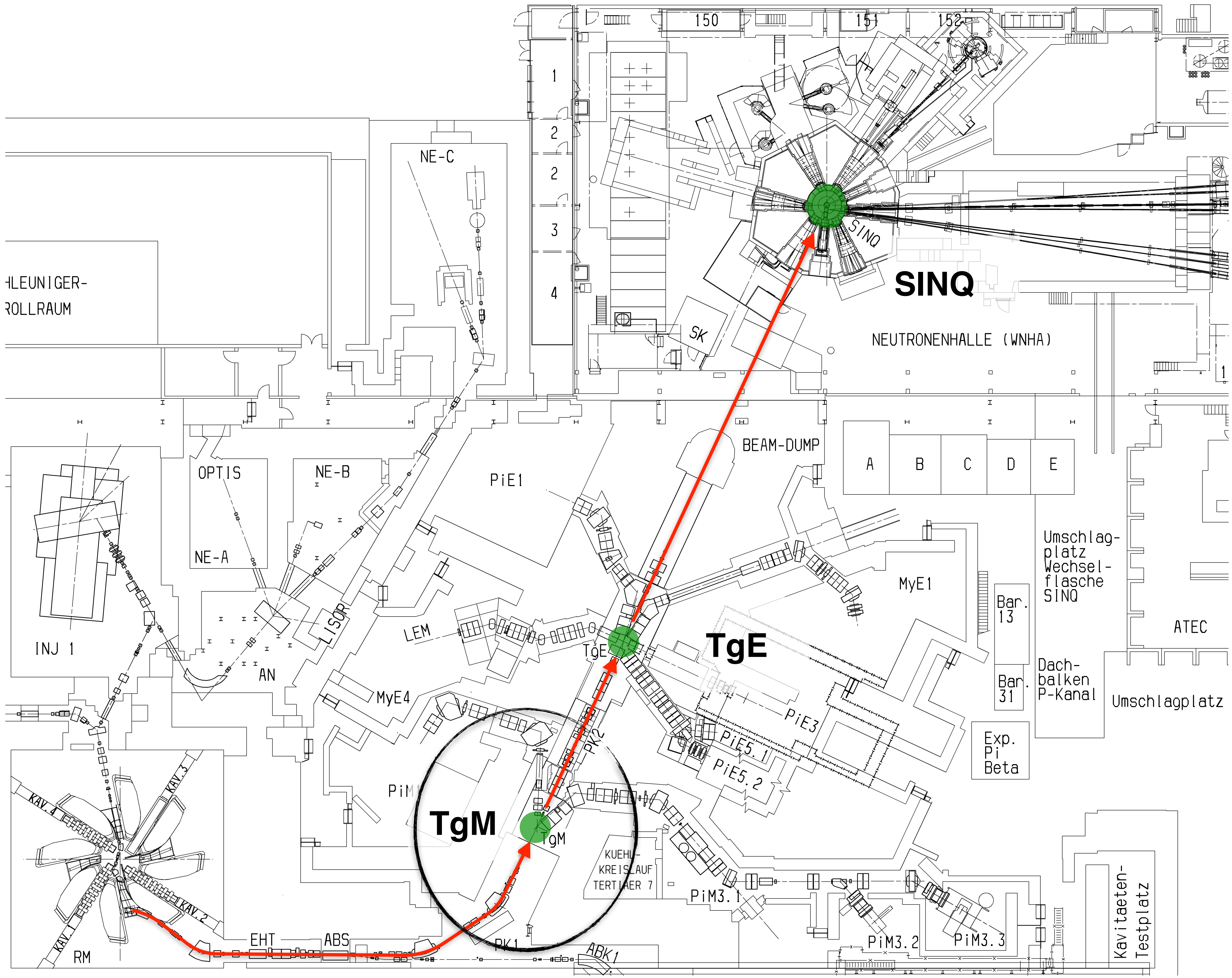
- Setup of proton beam well under control
- Increased safety margins confirmed



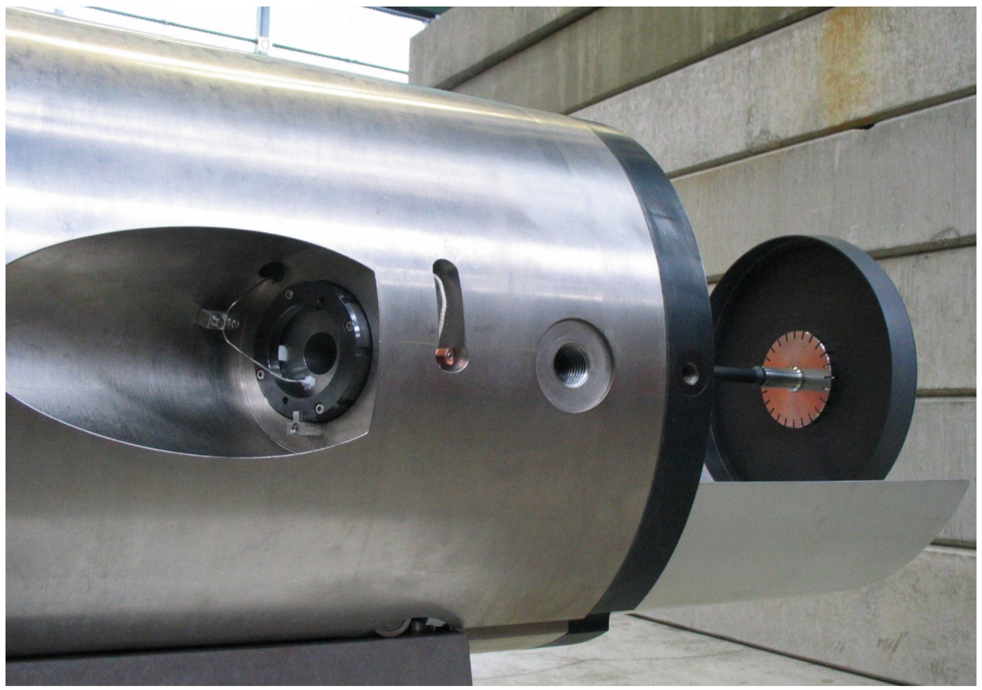
Future:

- To be seen: Impact of higher thermal stress on long term stability of target wheel. HIMB target has been running all of 2020 until recent target change due to failure of bearings.

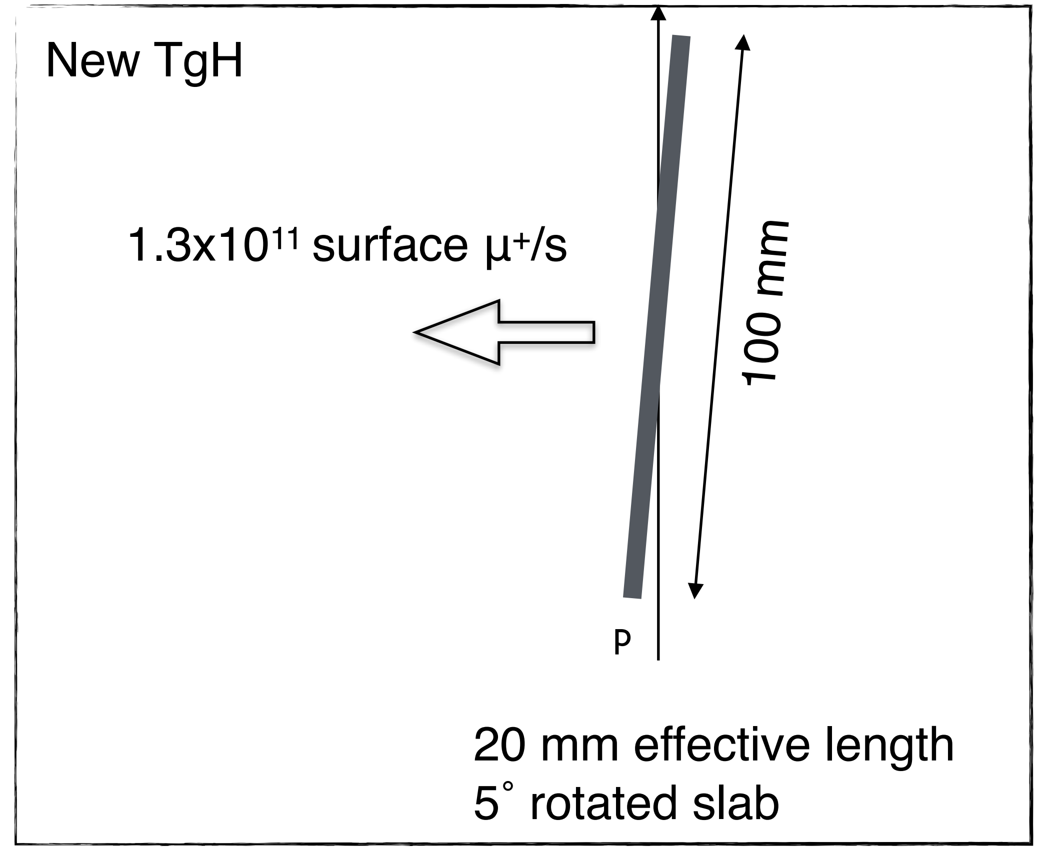
Floorplan PSI



Target Geometry for new TgH

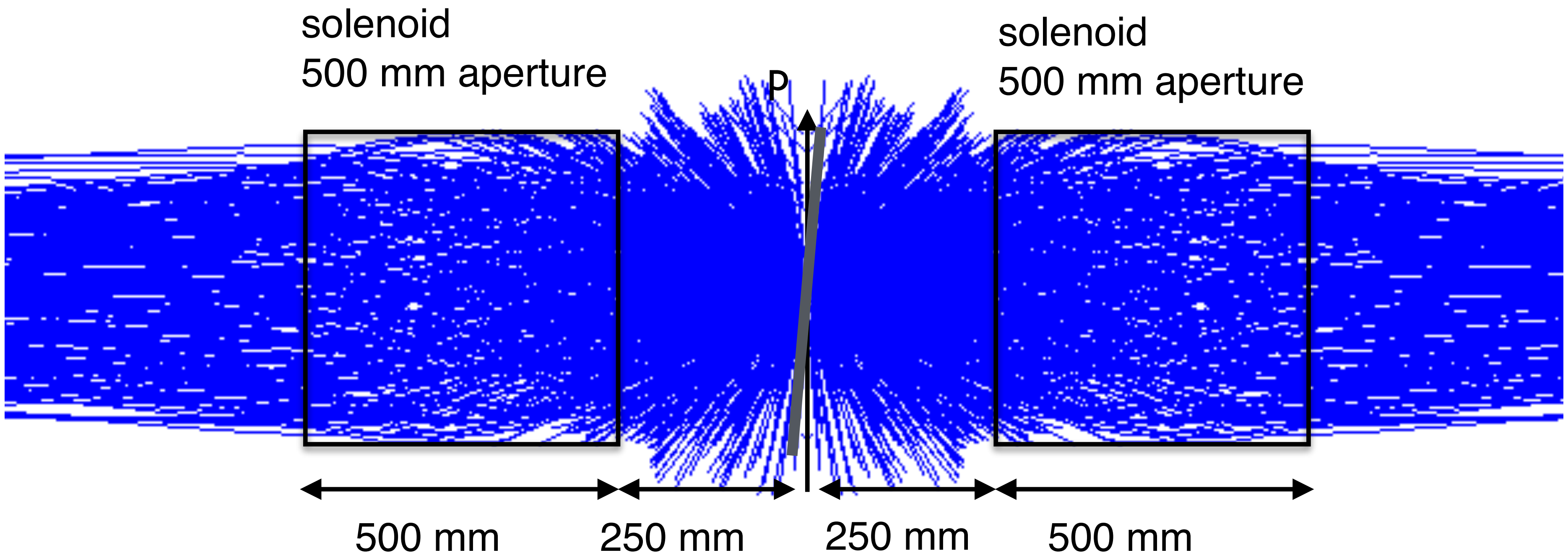


Existing TgM

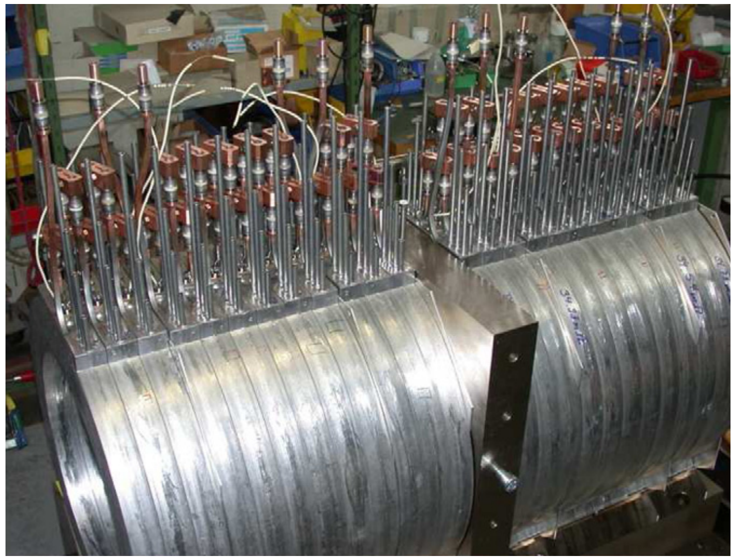


- Change current 5 mm TgM for 20 mm TgH (known situation from 60 mm TgE)
- 20 mm rotated slab target as efficient as 40 mm standard Target E

Split Capture Solenoids

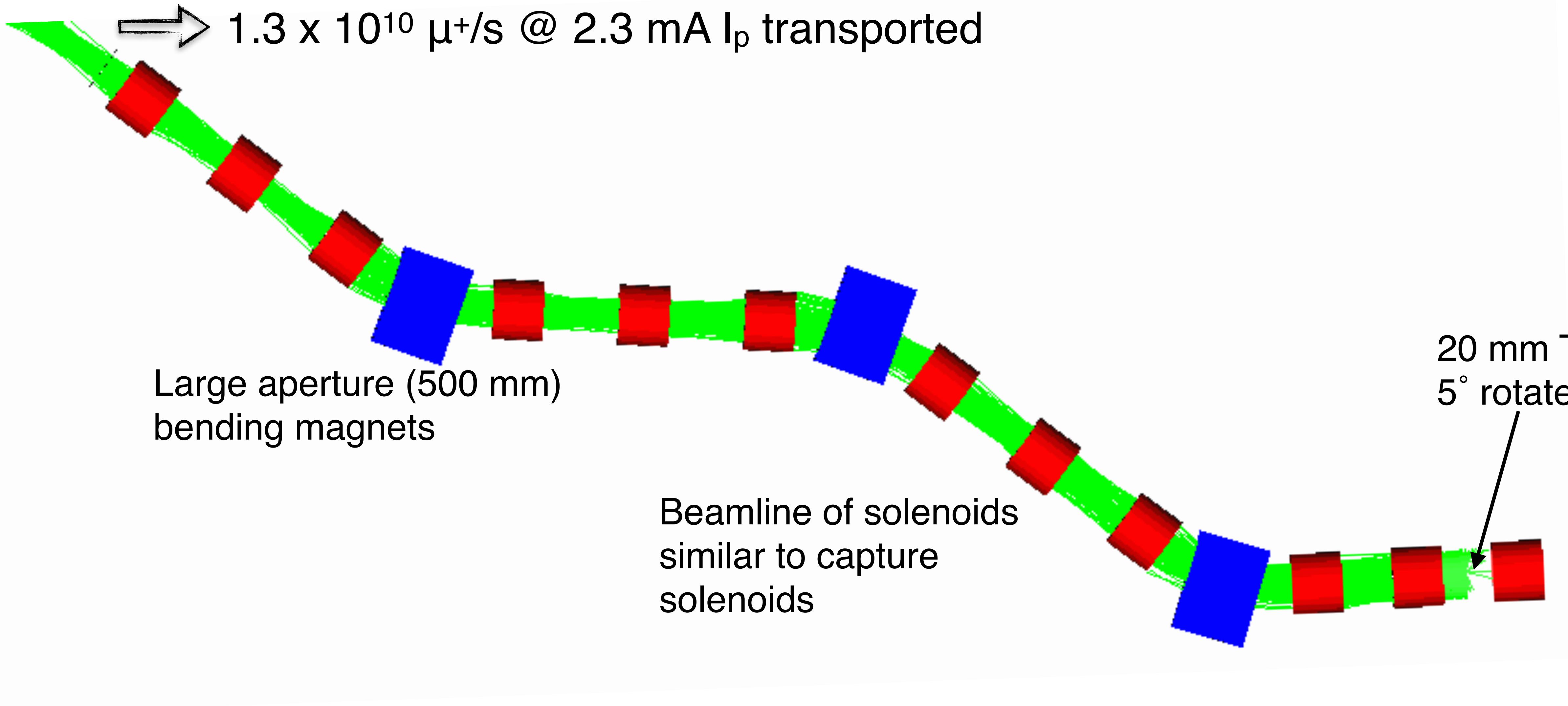


- Two normal-conducting, radiation-hard solenoids close to target to capture surface muons
- Central field of solenoids ~0.35 T



Capture solenoids very similar to existing μE4 solenoids

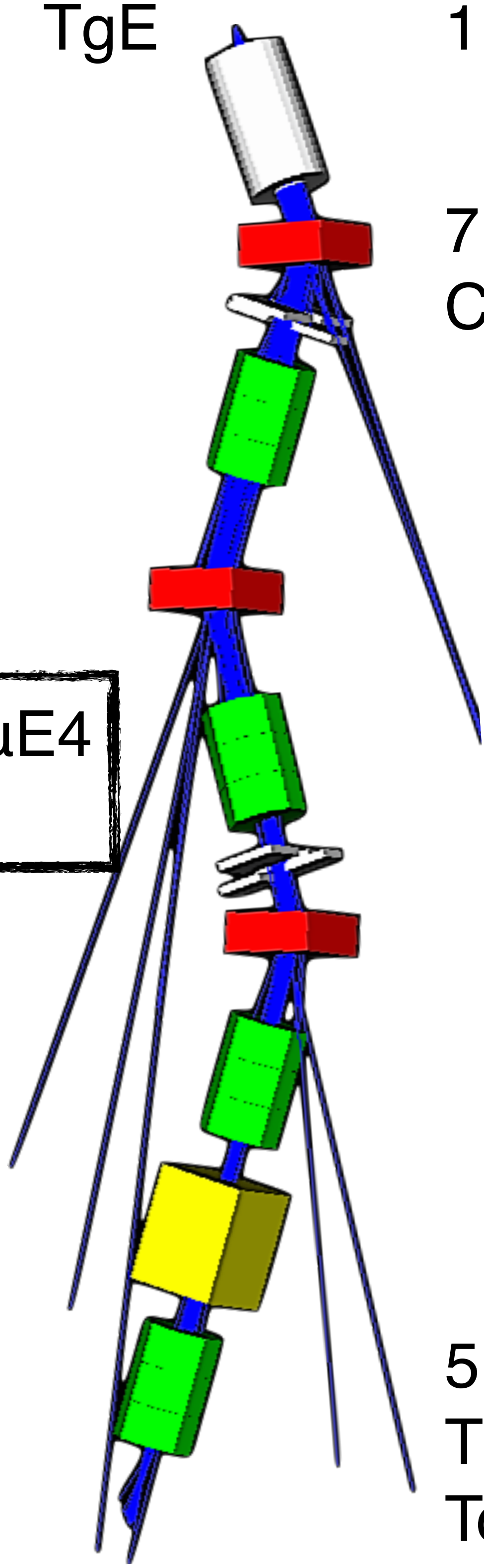
Solenoid Beamline



- First version of beam optics in a generic long beamline showing that large number of muons can be transported.
- Almost parallel beam, no focus, no separator, …

Solenoid Beamline

TgE

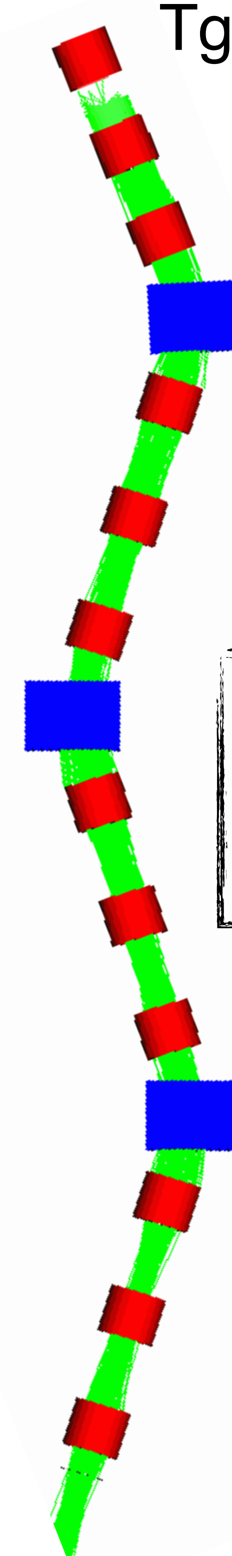


Existing μE4 beamline

TgE		TgH
1.2×10^{11} μ+/s	Source	1.3×10^{11} μ+/s
7.2×10^{9} μ+/s C ~ 6%	Capture	3.4×10^{10} μ+/s C ~ 26%
5×10^{8} μ+/s T ~ 7% Total ~ 0.4%	Transmission	1.3×10^{10} μ+/s T ~ 40% Total ~ 10%

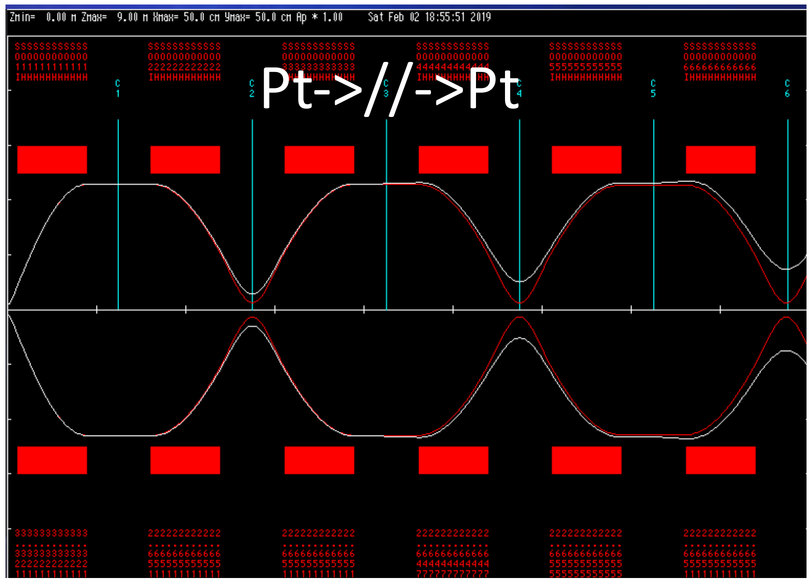
⇨ Gain due to high capture and transmission efficiency

TgH

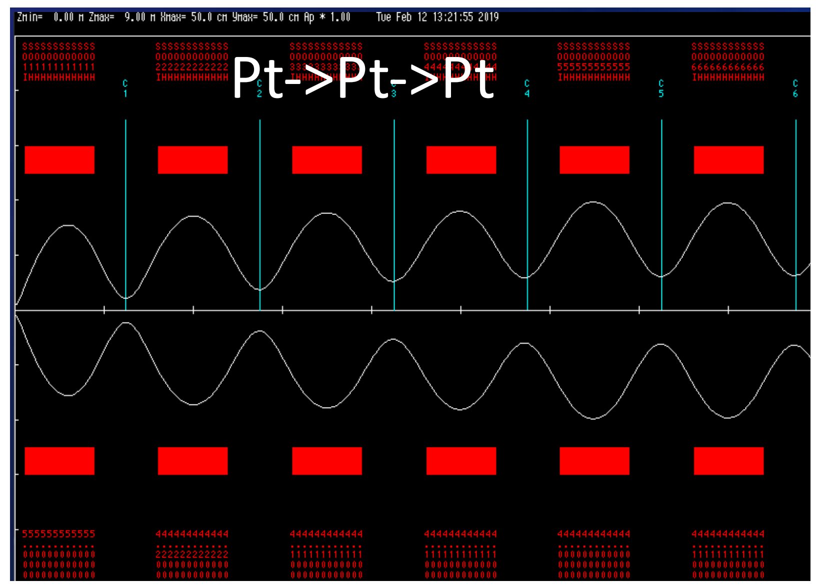


Proposed solenoid beamline

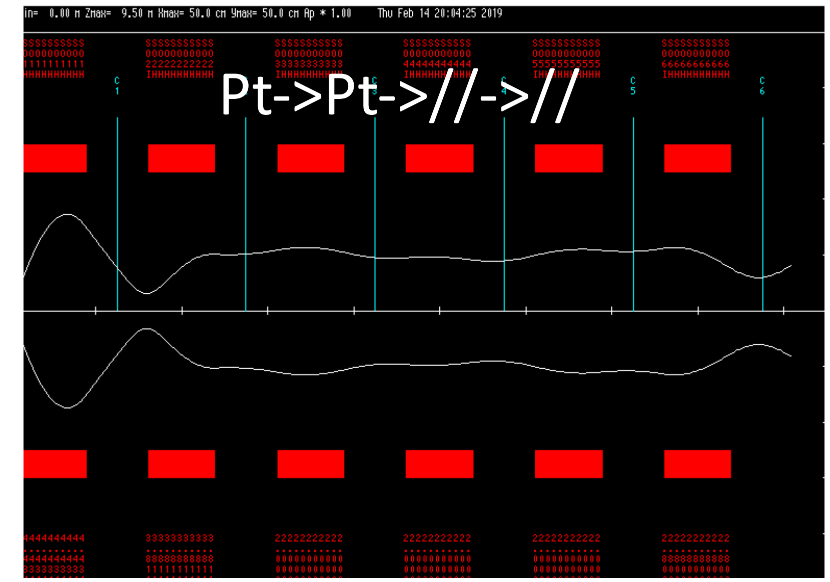
Study of different beam optics



	ALL SM		
capture	transmission	Total	Rate/s @2.4mA
0.25	0.43	0.11	1.50E+10
	SM(25.48-29.79) Only		
capture	transmission	Total	Rate/s @2.4mA
0.19	0.54	0.10	5.71E+09



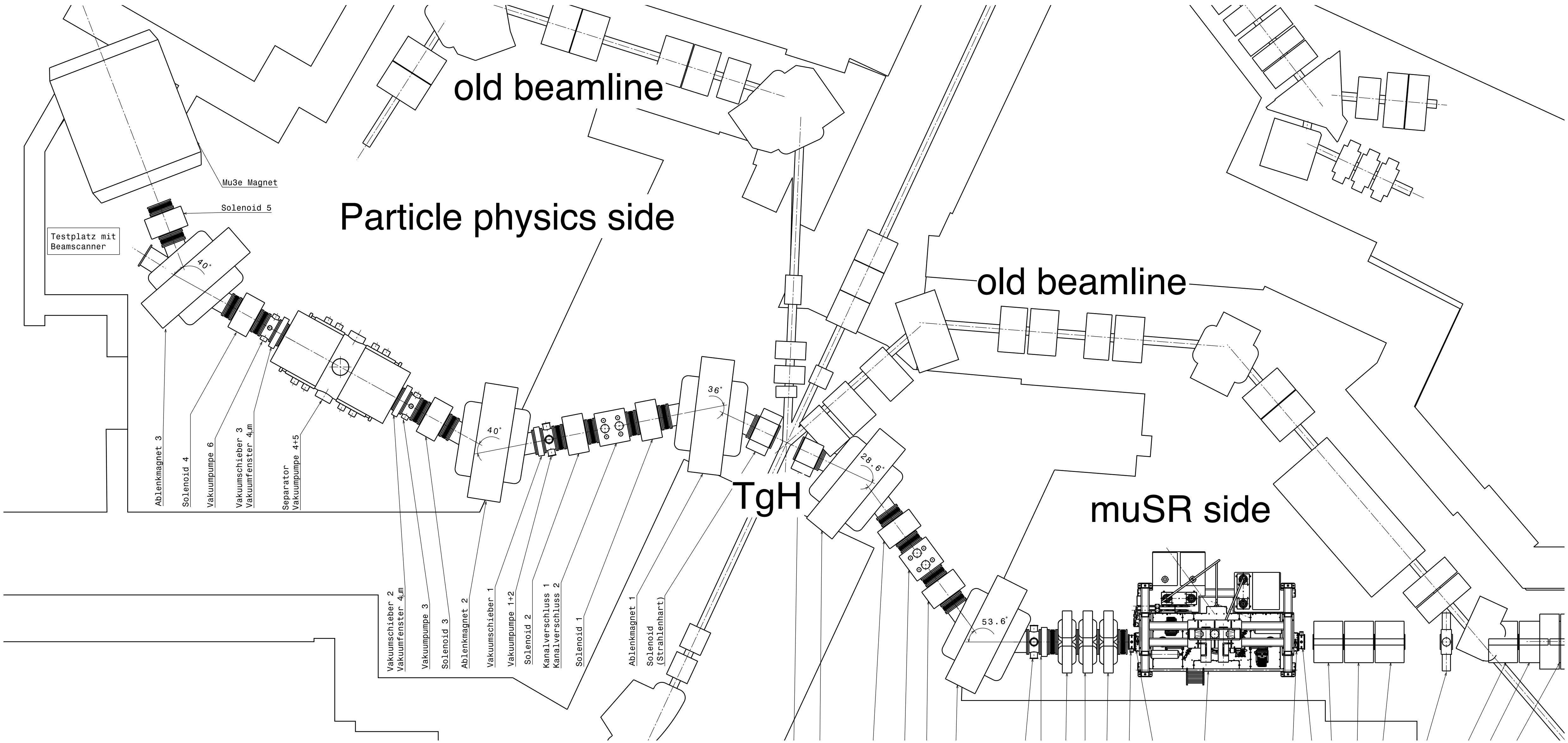
	ALL		
capture	transmission	Total	Rate/s @2.4mA
0.36	0.20	0.07	9.88E+09
	SM(25.48-29.79) Only		
capture	transmission	Total	Rate/s @2.4mA
0.32	0.48	0.15	8.45E+09



	ALL		
capture	transmission	Total	Rate/s @2.4mA
0.34	0.32	0.11	1.52E+10
	SM(25.48-29.79) Only		
capture	transmission	Total	Rate/s @2.4mA
0.29	0.69	0.20	1.12E+10

- Checked different beam optics both in TRANSPORT (matrix code) and G4beamline for long straight sections
- Around 10^{10} muons/s achieved in all cases. However, quite some differences between full momentum spectrum and momentum-bite performance
- In all versions, final beam spot typically quite large: $\sigma \sim 50$ mm
  → ways to decrease it currently under study

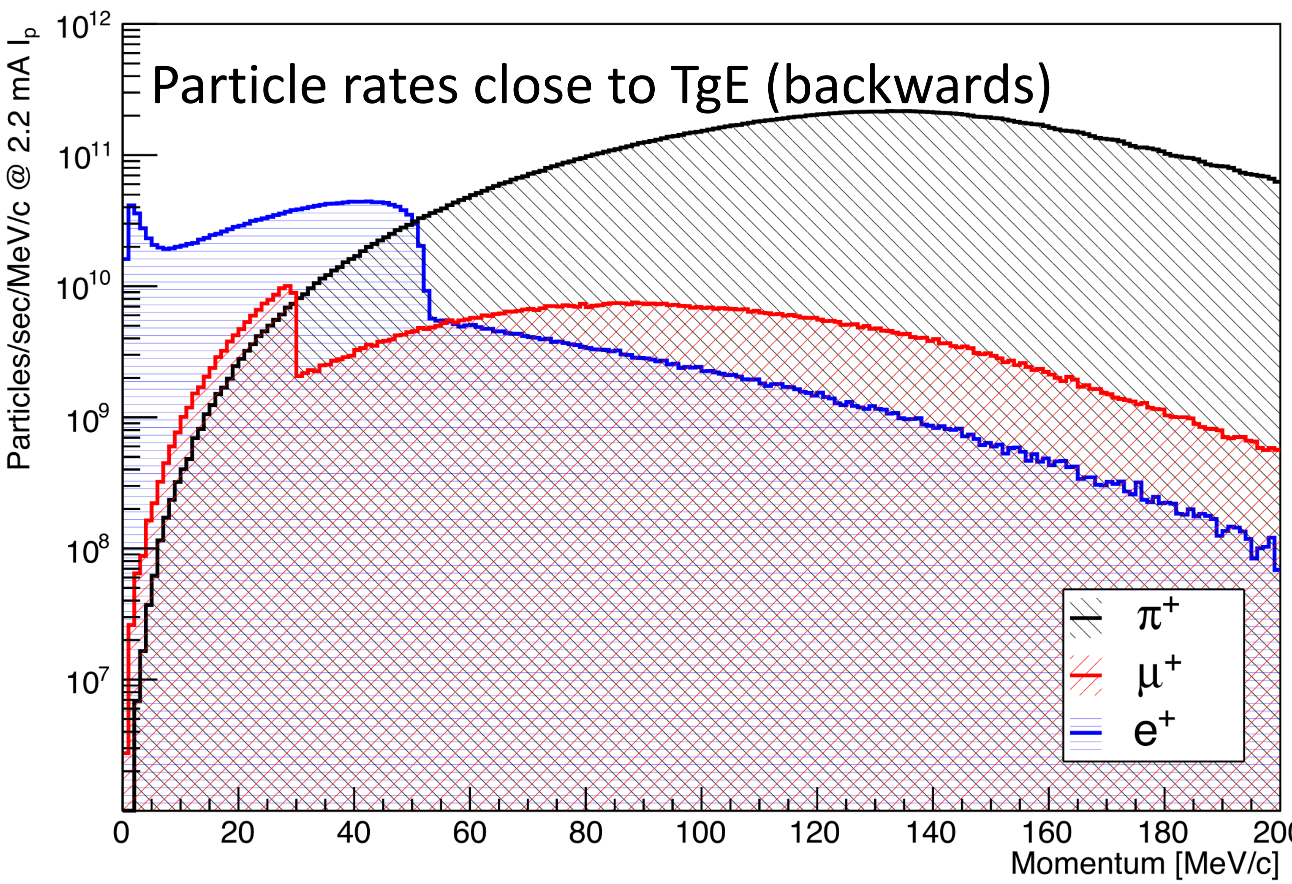
Towards realistic beamline layouts



- We now have more realistic beam layouts to simulate → currently ongoing
- Include necessary elements such as beam blockers etc.
- Full solenoid beamline towards particle physics side
- Coupling into triplet on muSR side

Beyond surface muons

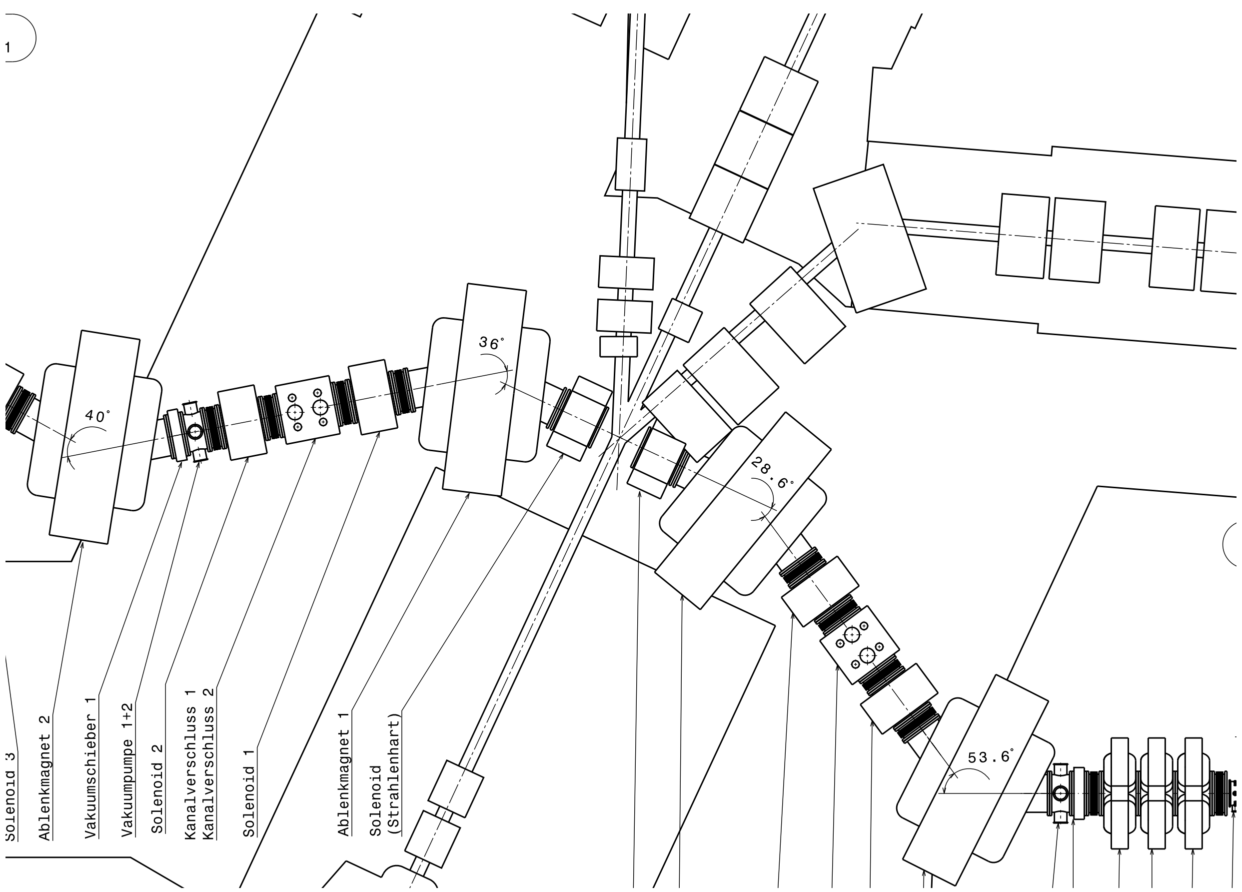
- HIMB is aimed at surface muons
- However, other particles are of course also of interest
- Will need to check their rates and properties:
  - Negative muons
  - Pure electron/positron beams
  - Pions (solenoids not ideal for high momentum)

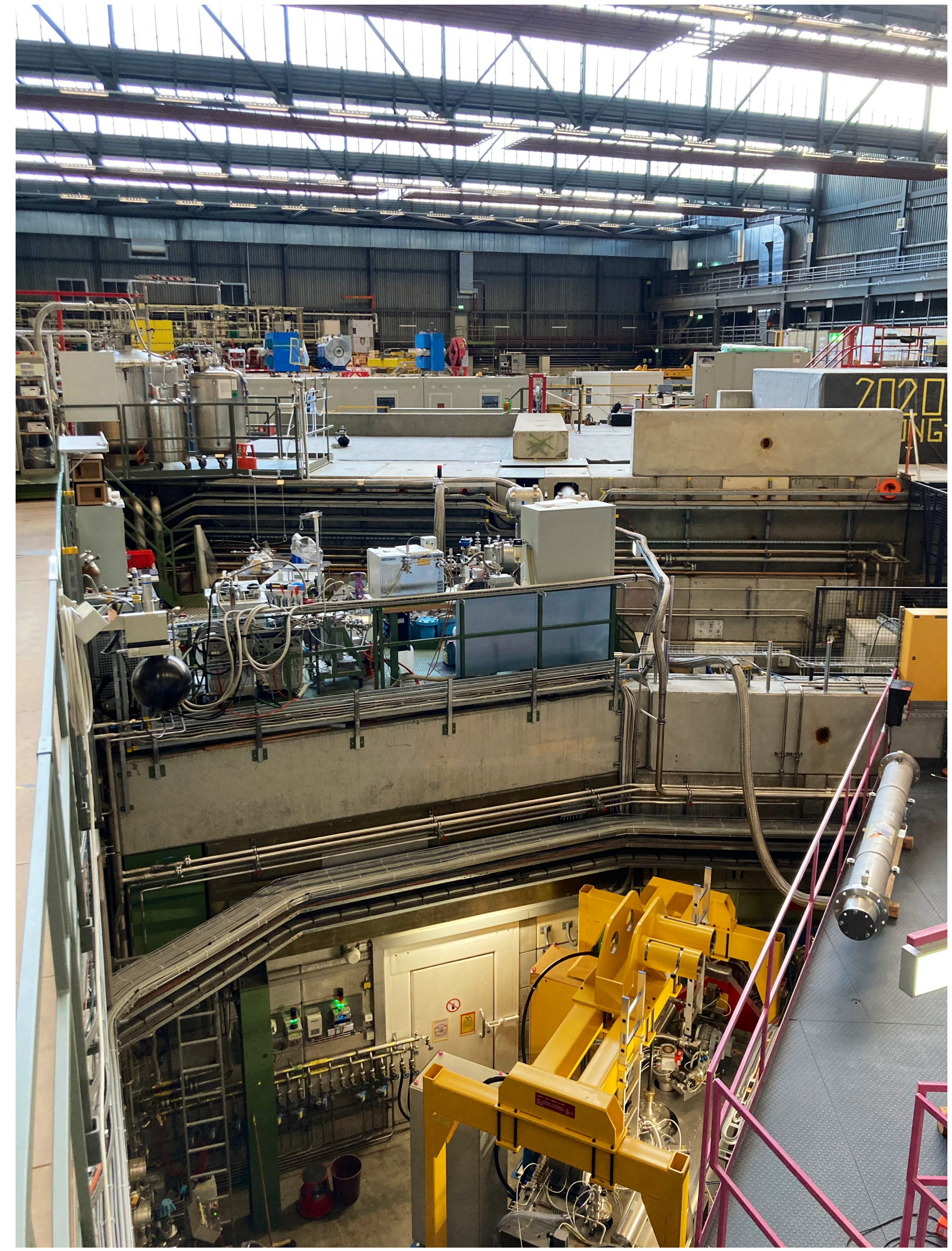


Hodge, Thesis (2018)

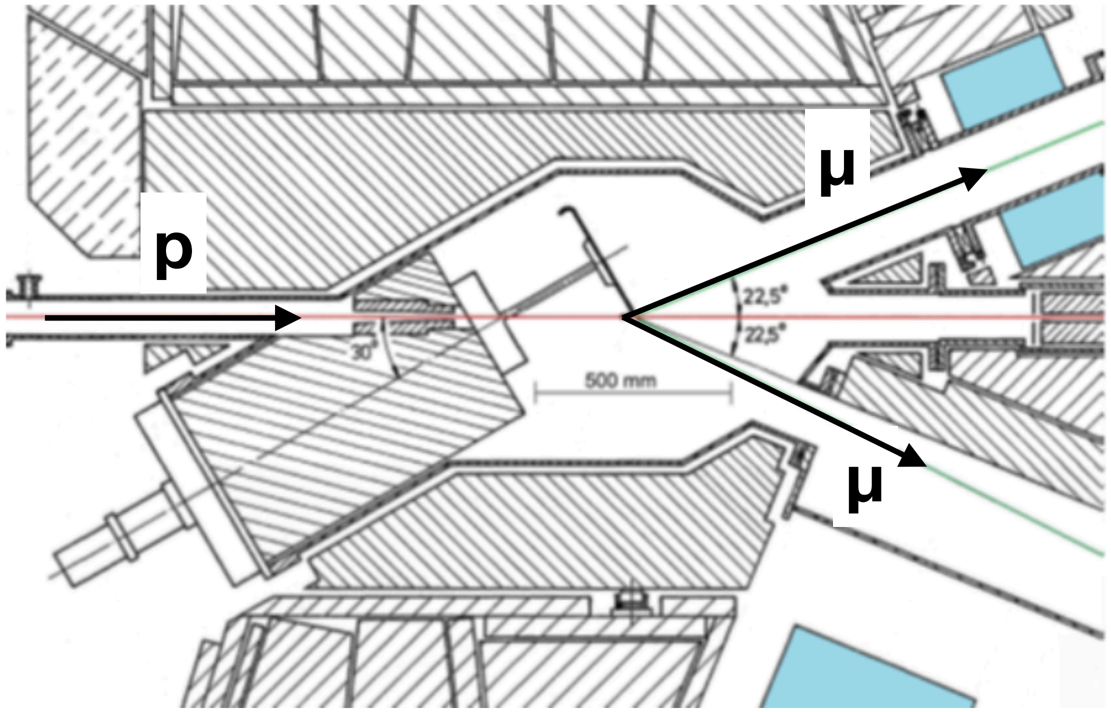
Building a new target station

- Challenging environment around TgM to change layout
- Helium liquefier, tertiary cooling loop 7, lots of pipes, cables and conduits, power supply platforms, …
- And of course in an environment with doses measured in Sv/h

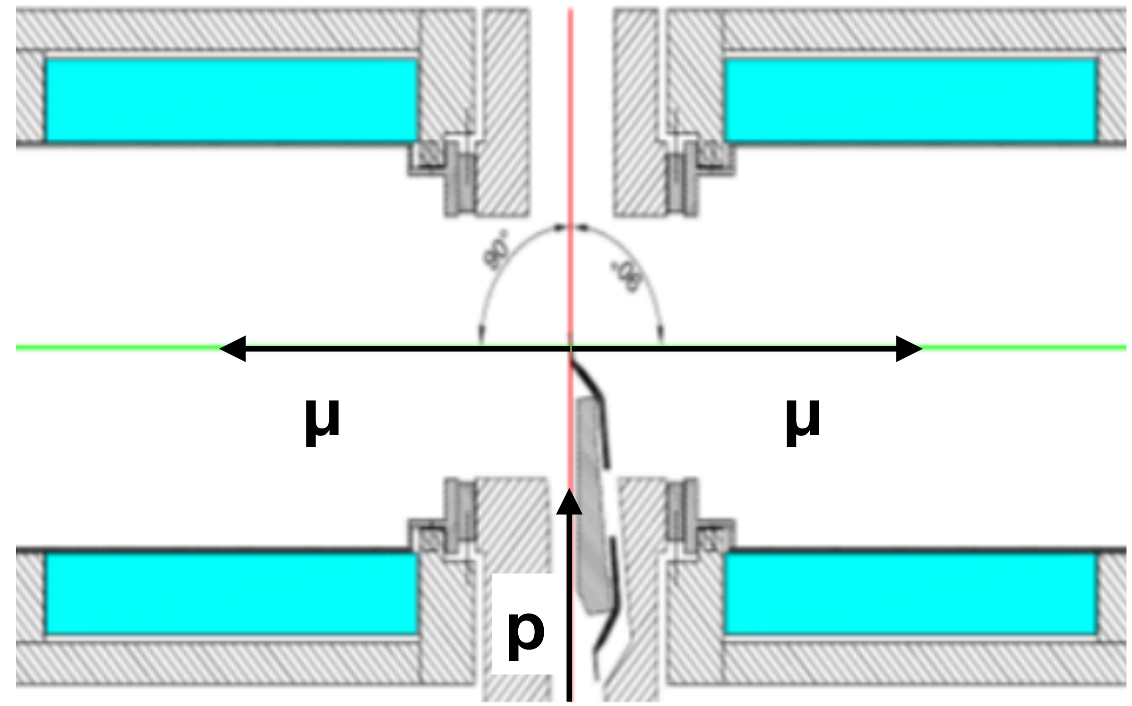




First ideas for new TgH design



Existing TgM

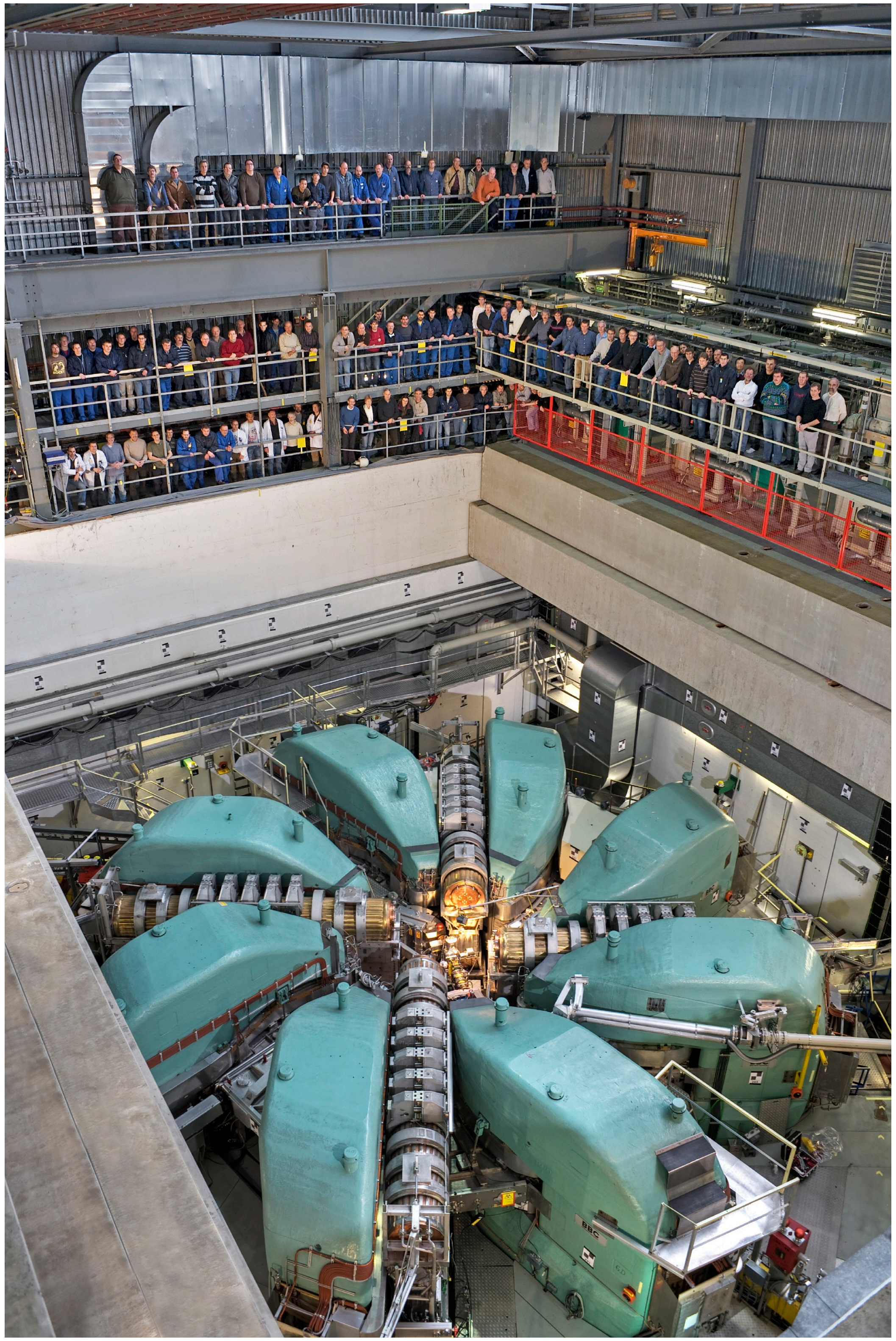


First concept for TgH

- Capture solenoids will need to come very close to the target wheel
- First concept available showing how this could be accomplished
- Alternative concept placing capture solenoids into the target vacuum chamber under development

Challenges!

- Main topics to study:
  - Exact position of new TgH
  - Impact on existing infrastructure
  - Proton beam optics and channel
  - Performance of solenoidal channel
  - Electron/muon separation
  - New target area & shielding design
  - Disposal of activated components
  - Science case



Conclusions

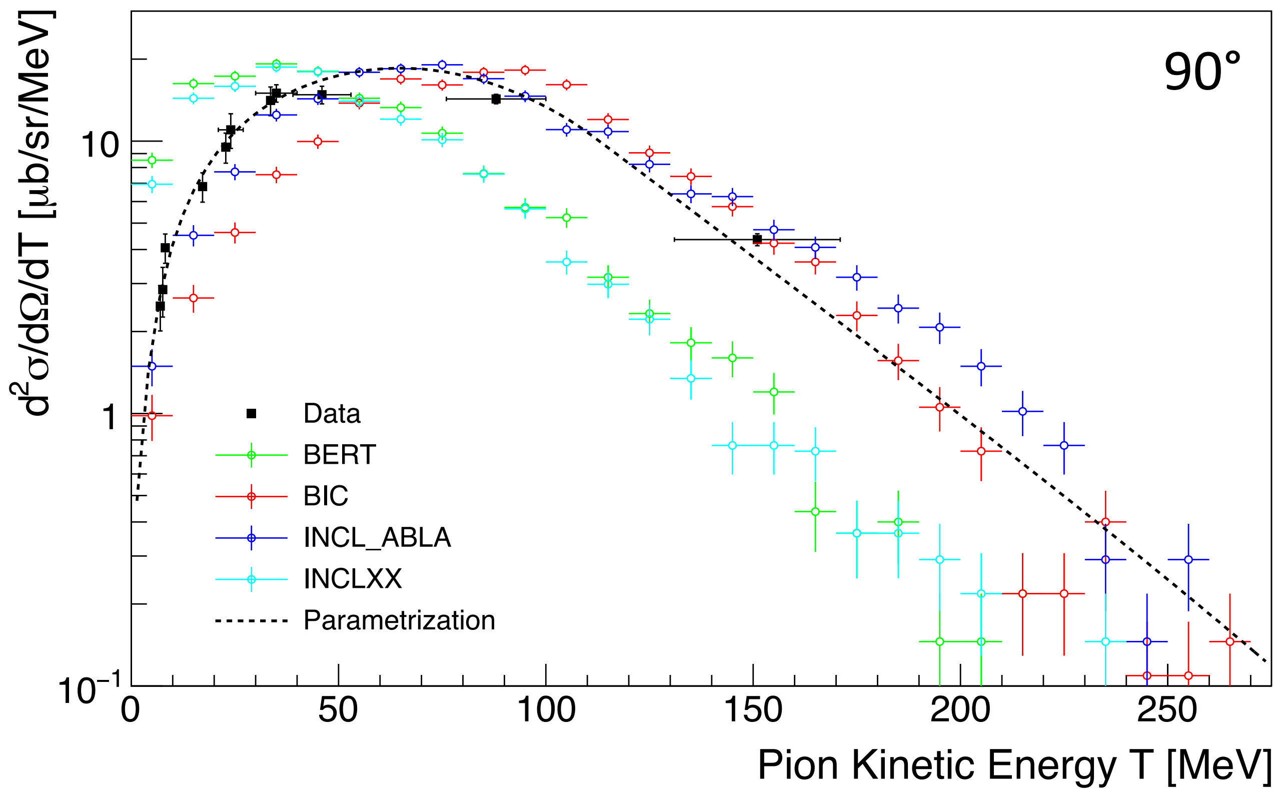
- Good prospects of achieving muon rates of 10^{10} mu^{+}/s at PSI
- HIMB will enable forefront muon research at PSI for the next 20+ years
- Important dates:
  - Science Case workshop 6-9 April 2021
  - CDR by end of 2021
  - Implementation during 2026/2027

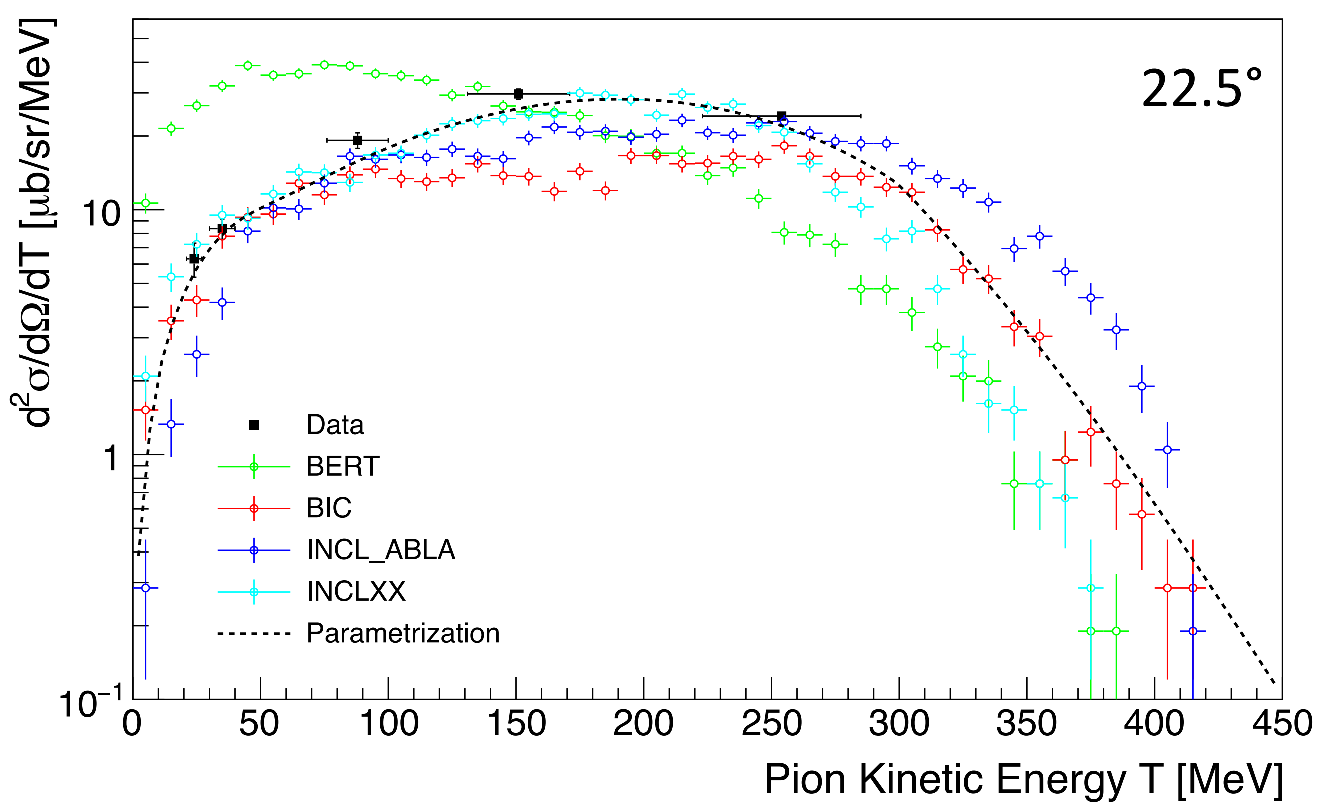
Backup

Simulation

- Implemented our own pion production cross sections into Geant4/G4beamline based on measured data and two available parametrizations
- Valid for all pion energies, proton energies < 1000 MeV, all angles and all materials
- Implemented “splitting” of pion production and muon decay to speed up simulation

⇨ Reliable results at the 10% level

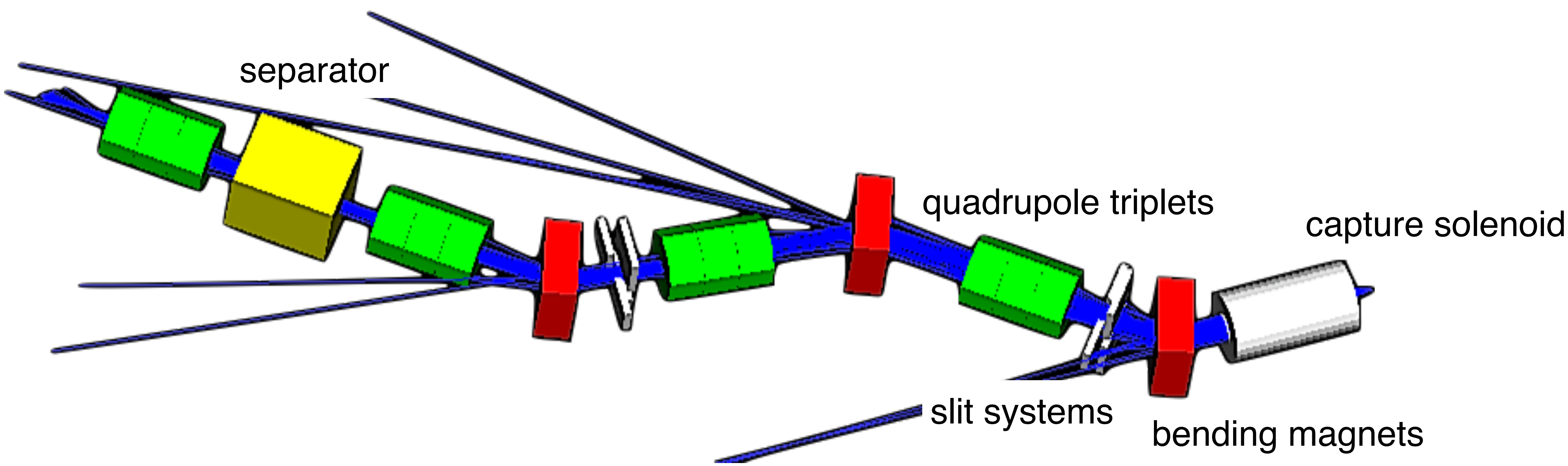




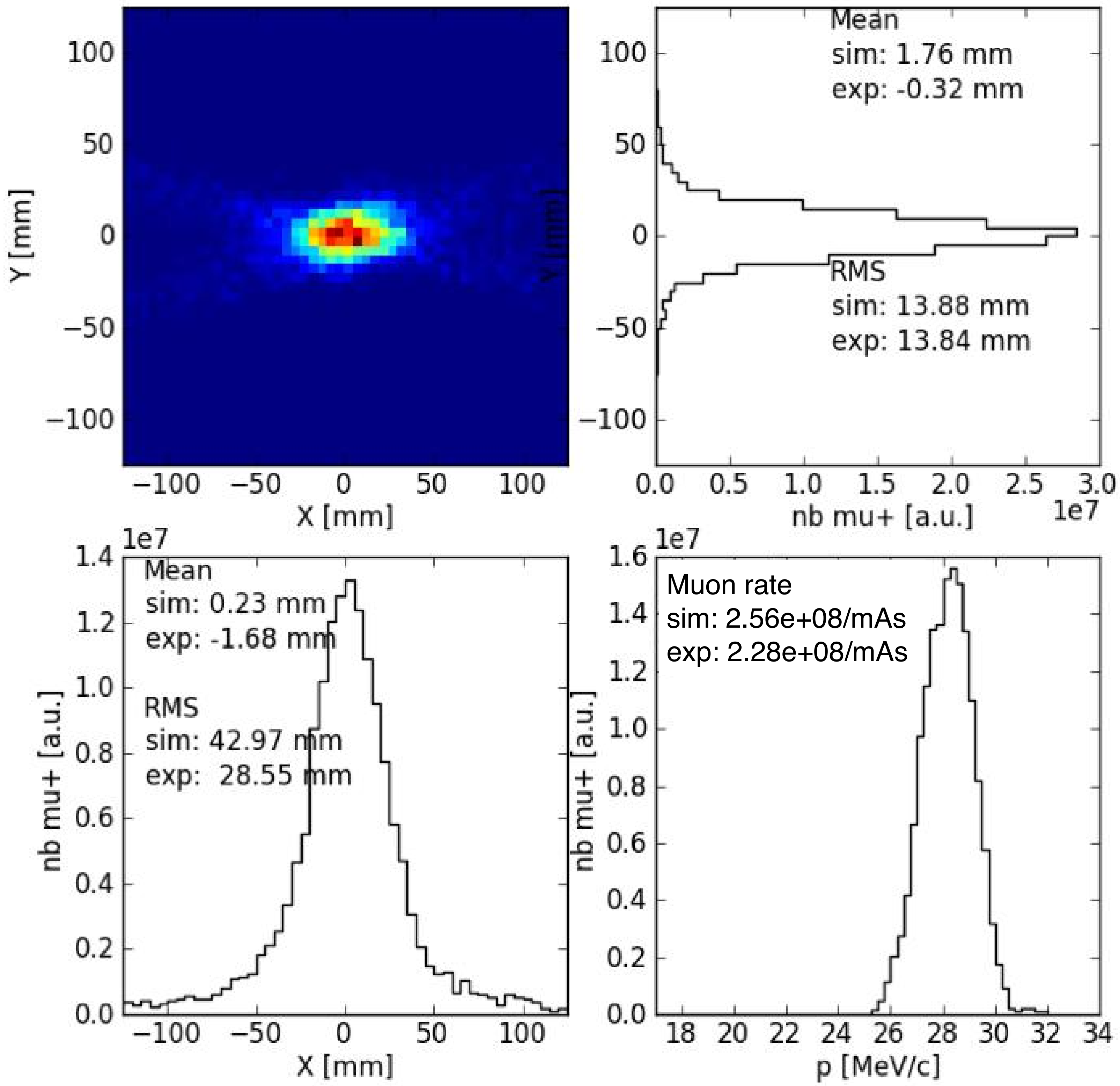
R. L. Burman and E. S. Smith, Los Alamos Tech. Report LA-11502-MS (1989)
R. Frosch, J. Löffler, and C. WIgger, PSI Tech. Report TM-11-92-01 (1992)
F. Berg et al., Phys. Rev. Accel. Beams **19**, 024701 (2016)

G4beamline simulation of muE4

- MuE4 beamline implemented into G4beamline
- Detailed field maps available for all elements (crucial!)
- Simulation starts from protons on Target E

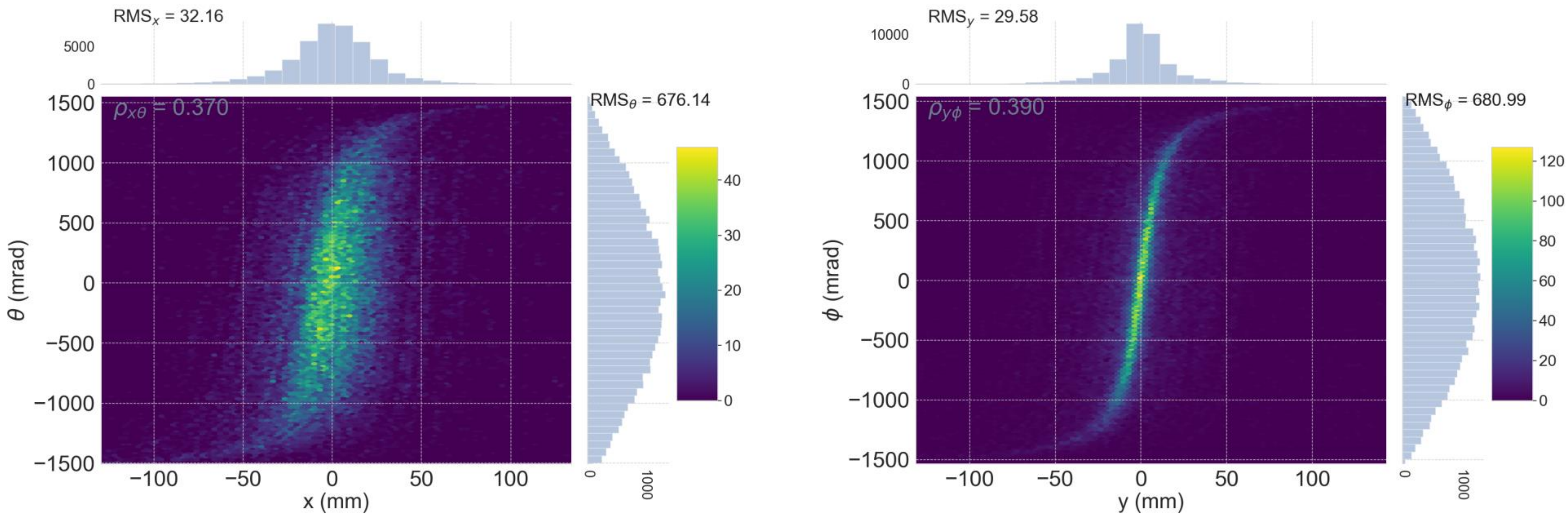


muE4 Rate & Beam Profile



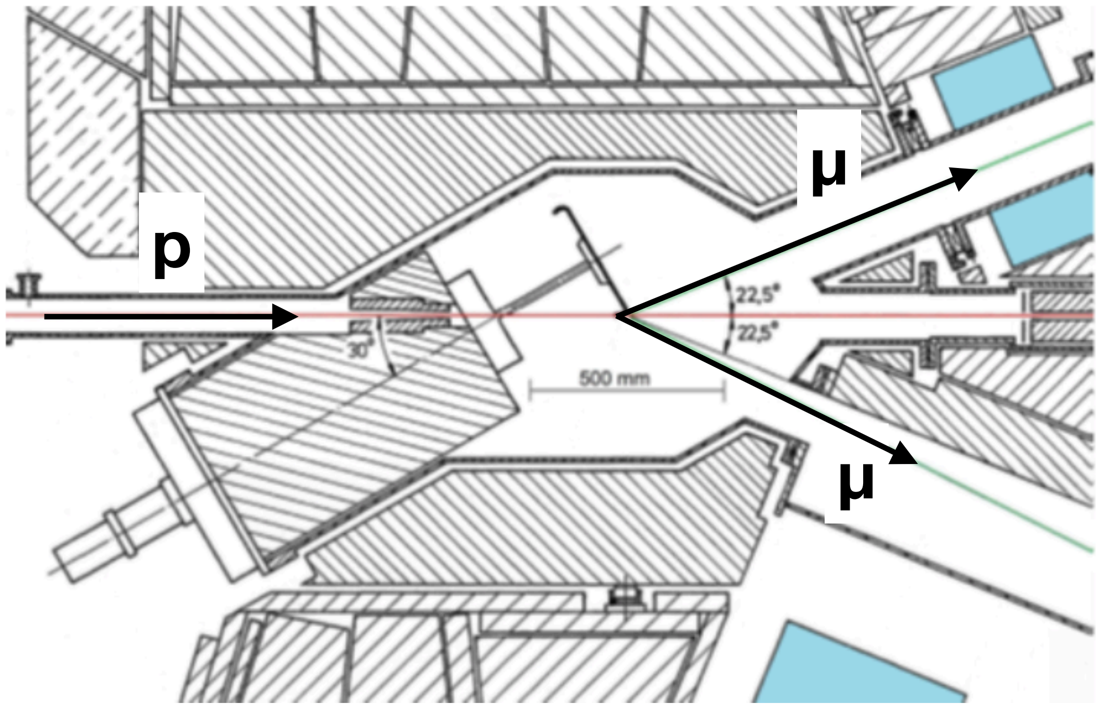
⇒ Excellent agreement between simulation and measurements

Source characteristics

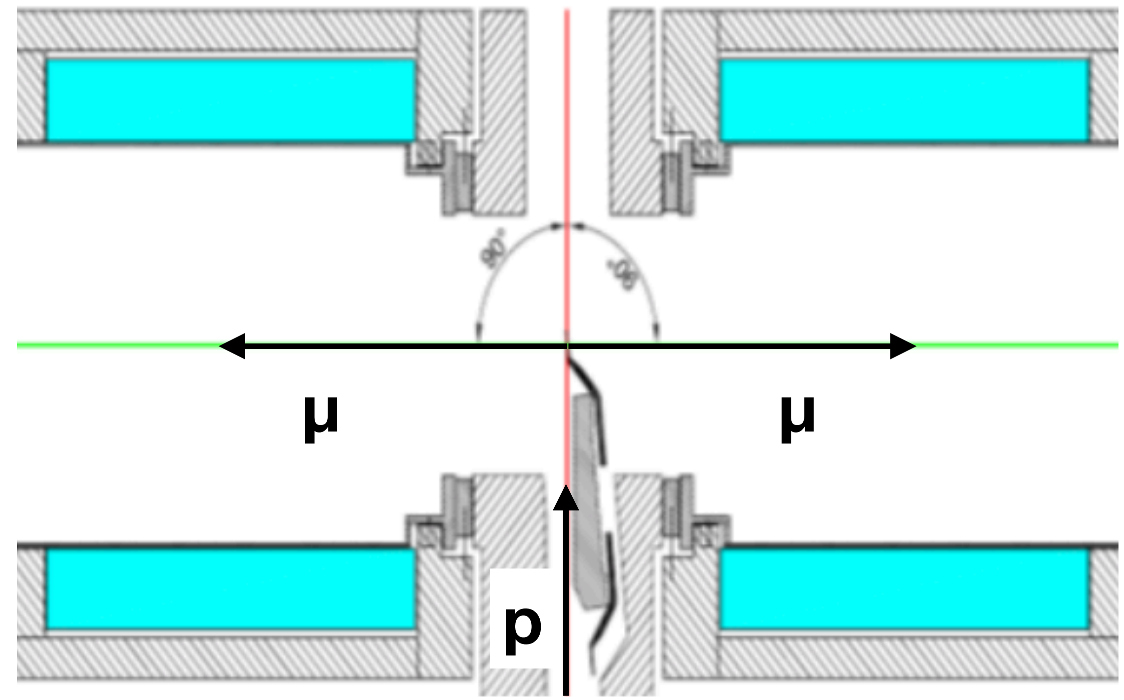


- Phase space of surface muons emitted from the target
- Spot size with σ ~ 30 mm in horizontal and vertical direction
- Emission of surface muons follows cos(theta)-distribution → allows to capture a large fraction of the emitted surface muons

First ideas for new TgM* design



Existing TgM

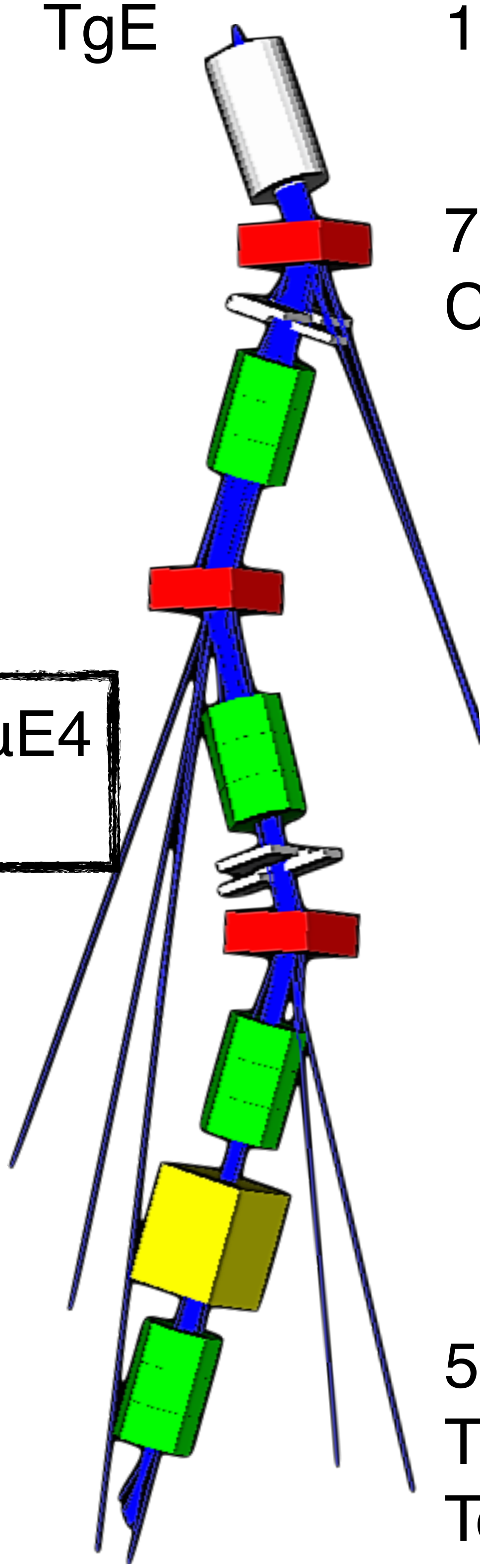


First concept for TgM*

- Capture solenoids will need to come very close to the target wheel
- First concept available showing how this could be accomplished
- Goal is to use the same exchange flask as TgE for target changes

Solenoid Beamline

TgE



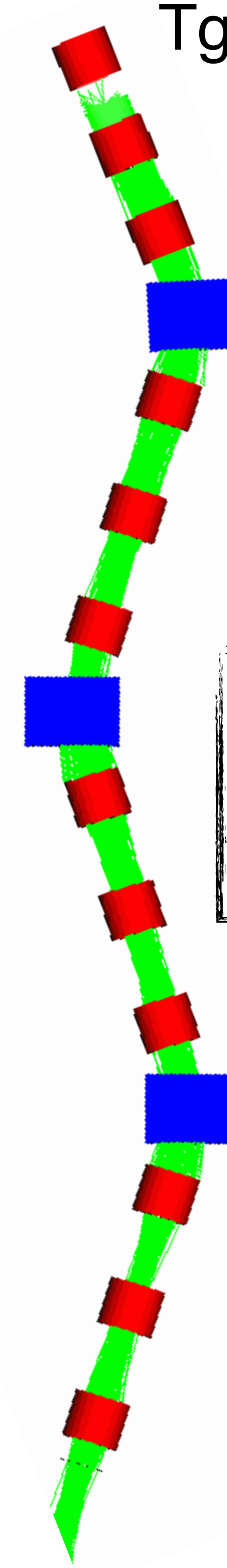
Existing µE4 beamline

	TgE		TgM*
Source	1.2 x 10^{11} µ+/s		1.3 x 10^{11} µ+/s
Capture	7.2 x 10^{9} µ+/s C ~ 6%		3.4 x 10^{10} µ+/s C ~ 26%
Transmission	5 x 10^{8} µ+/s T ~ 7% Total ~ 0.4%		1.3 x 10^{10} µ+/s T ~ 40% Total ~ 10%

⇨ Gain due to high capture and transmission efficiency

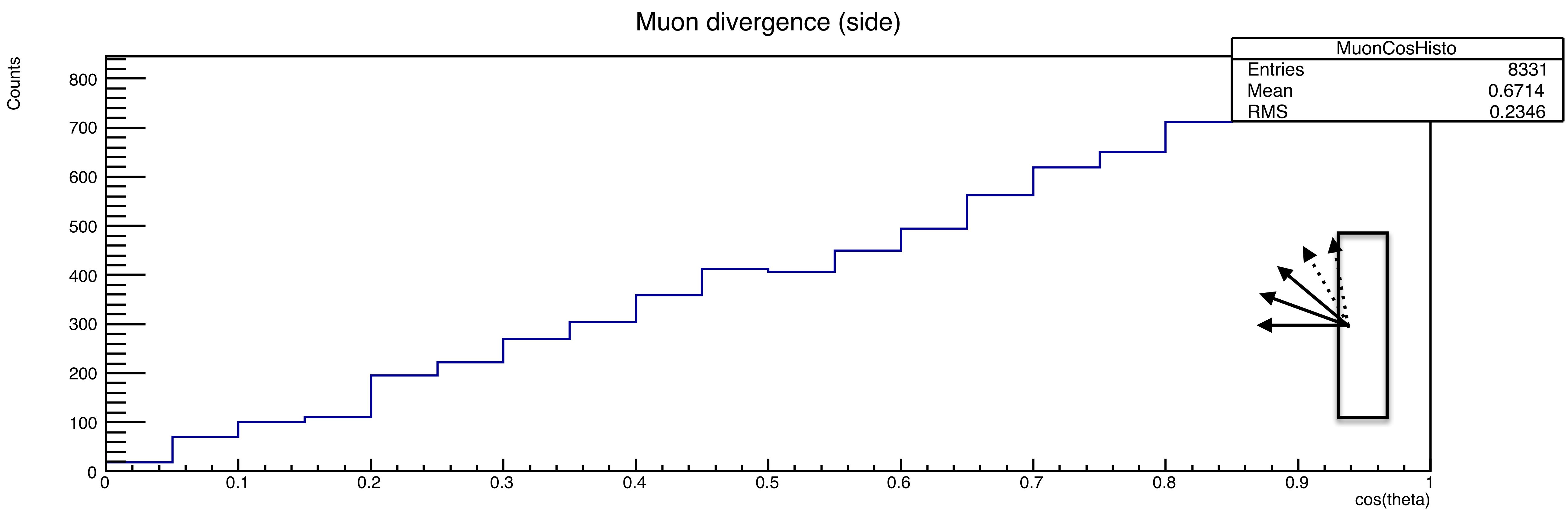
⇨ Expect around 5x10^{7} µ-/s at 28 MeV/c

TgM*



Proposed solenoid beamline

Surface Muons Are Nice!



- Surface muons are not emitted isotropically but preferentially perpendicular to the surface
- Polarisation also follows this distribution. Even for all surface muons and initial divergence have 67% polarization

Simple simulation for polarisation

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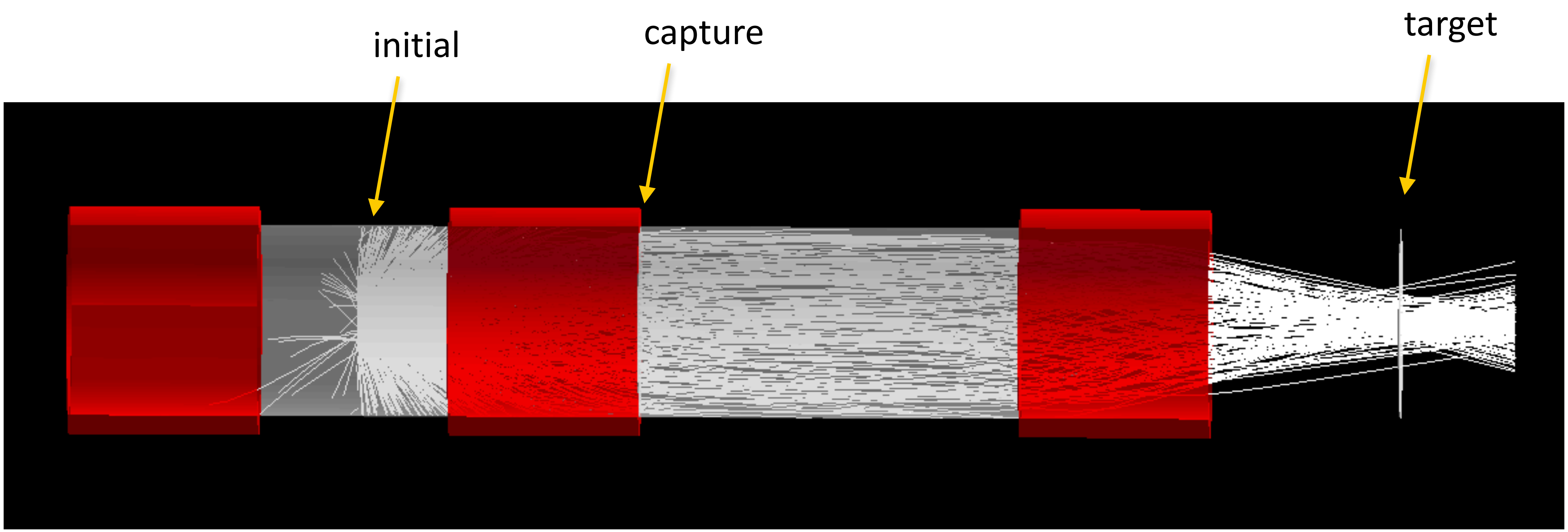
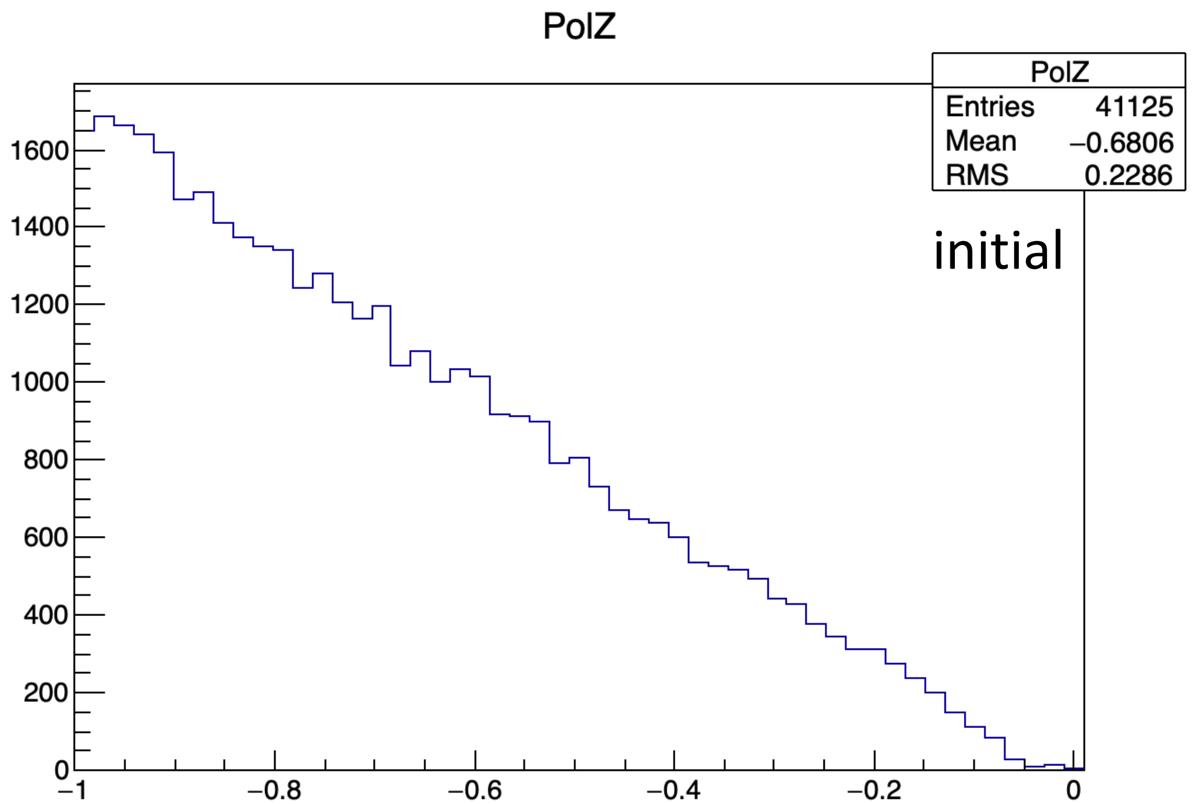
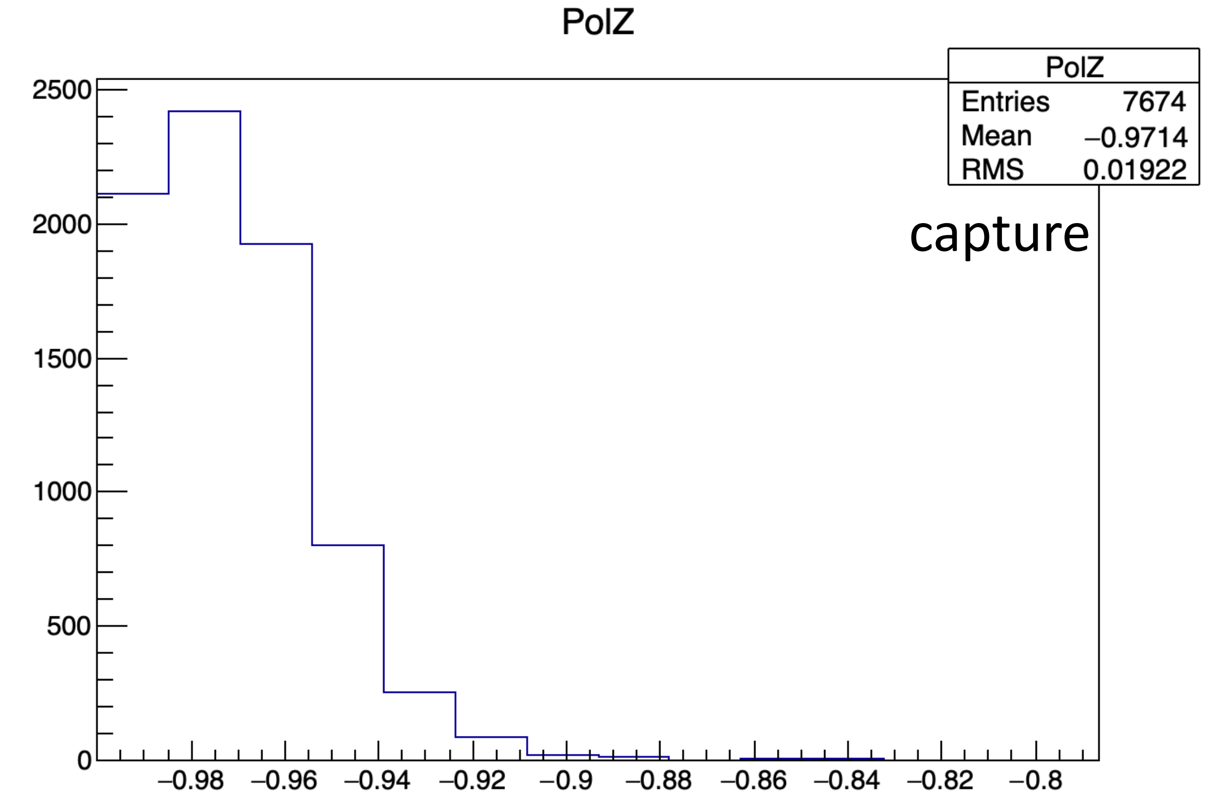
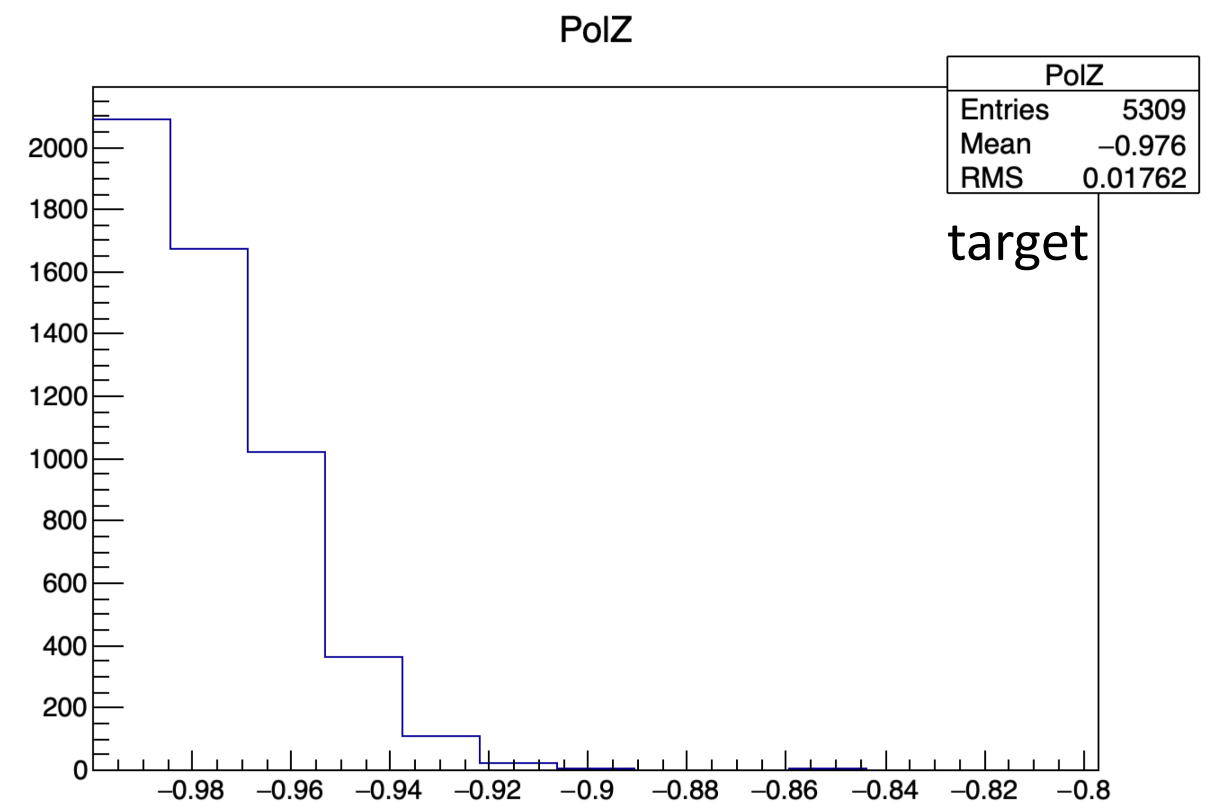


- Capture solenoids at 250 mm from target
- Gap of 1000 mm in between solenoids
- Approximate focus 500 mm away from last solenoid
- Sampled polarisation at 3 positions

Polarisation from the simulation

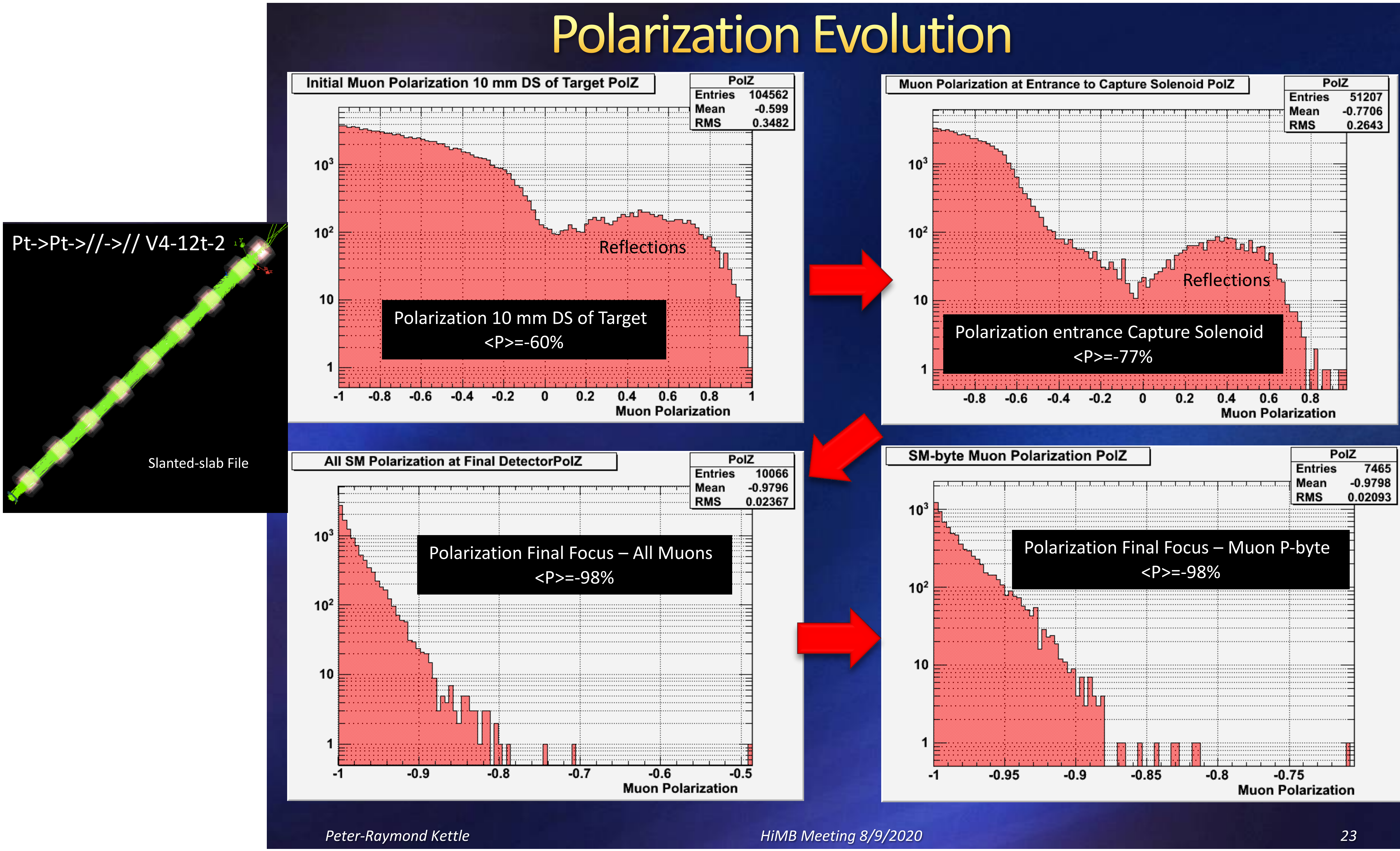






- Initial polarisation of the beam of 68% is increased to 97% after the capture in the solenoid
- High polarisation is also achieved at the final focus
- From other simulations we know that we transport a few % of cloud muons
  → expect about 95% total polarisation

Polarisation in a long solenoid beamline



Phase space

- muE4 (full phase space):
  horizontal emittance: ~ 5500 mm*mrad
  vertical emittance: ~ 10'000 mm*mrad

- piE5 (1-sigma):
  horizontal emittance: ~ 1200 mm*mrad
  vertical emittance: ~ 400 mm*mrad

- HIMB expected (1-sigma):
  horizontal emittance: ~ 7000 mm*mrad
  vertical emittance: ~ 7000 mm*mrad

muE4

Table 4
Summary of μE4 beam properties at LEM moderator target, 28 MeV/c, "WSX-on", 4-cm thick muon production target E

	Experiment	TRACK simulation
Accepted solid angle		135 msr
Horizontal emittance		550 π cm mr
Vertical emittance		1000 π cm mr
x/x' (FWHM)	6.5 cm	6.5 cm/150 mr
y/y' (FWHM)	2.8 cm	2.6 cm/300 mr

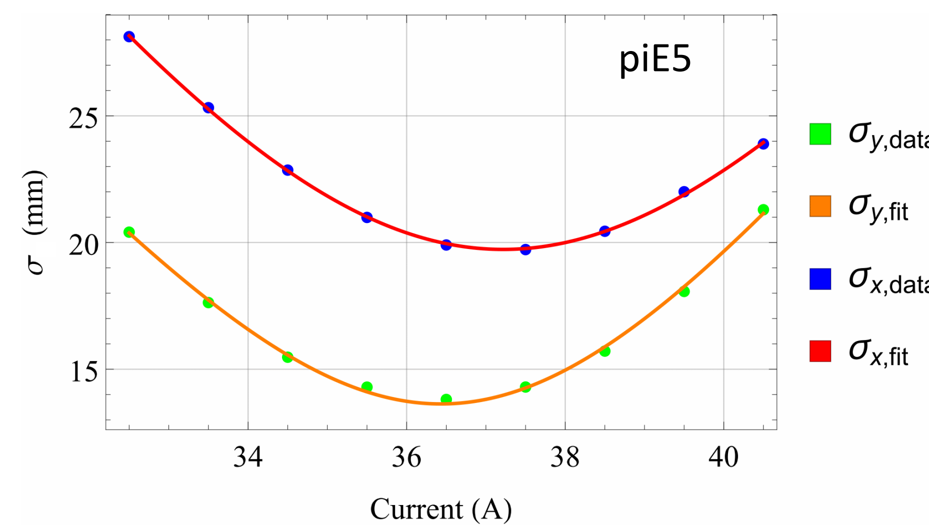


Figure 2.56.: *By changing the quadrupole currents of the QSK43 the size of the beam spot changes. The lines in the plot represent the expectations from the fitted phase space and a good agreement can be observed. The reconstructed phase space parametres are:* α_x=-4.06354, β_x=2.7613 m, ϵ_x=1163 mm·mrad, x_m=56.7 mm, θ_m=85.9 mrad, $\rho_{x\theta}$=0.9710 – α_y=18.7133, β_y=9.01 m, ϵ_y=426 mm·mrad, y_m=62.0, ϕ_m=128.8 mrad, $\rho_{y\phi}$=-0.9986